A Comparative Water Quality Study of Cheney Reservoir, Kansas

Final Report to the City of Wichita Water and Sewer Department

by

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Introduction and Background

Cheney Reservoir is a eutrophic water supply reservoir in south central Kansas, located near the city of Wichita. This reservoir was created by the U.S. Bureau of Reclamation in 1962 as an impoundment of the North Fork Ninnescah River, and serves as the principal source of drinking water for the city. It is large (40 km^2 in surface area at normal pool levels), has a maximum depth of 15 meters near the dam, and has an average depth of 5.3 meters at normal pool elevation (U.S. Fish and Wildlife Service 1996; J. Blain, pers. comm.). Following reports of undesirable taste and odor problems in the early 1990's, the U.S. Bureau of Reclamation and the City of Wichita initiated a 12 month study of water quality in the reservoir (U.S. Fish and Wildlife Service 1996). This study concluded that Cheney Reservoir was eutrophic, and that nuisance algal blooms could occur during the growing season. In addition, Cheney Reservoir has been included since 1985 in a lake and wetland monitoring program by the Kansas Department of Health and Environment (KDHE), which has made periodic measurements of its water quality (Carney 2001). The U.S. Geological Survey has performed analyses of sediment chemistry (Pope 1998) and fecal coliform bacteria in the Cheney Reservoir watershed (Mau and Pope 1999). Unfortunately, however, no direct or indirect measurements of taste and odor have been apparently made in any of these previous research programs, and these studies thus do not allow us to draw conclusions about possible links between observed taste and odor problems and the measured limnological characteristics of Cheney Reservoir.

Once they are produced in a reservoir, the monetary costs of drinking water treatment required to control taste and odor can be very high (Wnorowski 1992). For example, the costs of treating drinking water from eutrophic Lake Manatee, Florida with activated carbon exceeded $14,000 per day. Similarly, Blain (2001) compared the costs of five different taste and odor treatment methods for water drawn from Cheney Reservoir, which ranged from $44,000 to $712,800 per year. These examples emphasize the importance of developing a practical framework for Cheney Reservoir and its watershed that will help water quality managers to proactively minimize the intensity and the duration of taste and odor problems in the City of Wichita's water supply system, and will help keep water treatment costs down. The purpose of the research program reported here was to generate new data that can be used to develop predictive tools that can be used to help guide future water quality planning by the City of Wichita's Water and Sewer Department.

Scientific background to the problem. Taste and odor problems are a common symptom of eutrophic surface waters worldwide (Welch 1992; Smith 1998; Smith et al. 1999). This very undesirable result of nutrient enrichment is caused primarily by the presence of volatile organic molecules such as geosmin (trans-1, 10 dimethyl-trans-9-decalol), 2-methylisoborneol (MIB), and other compounds in the water column (Wnorowski 1992). These taste and odor-producing compounds can be produced by many microorganisms, including planktonic algae, benthic algae, and actinomycete bacteria (Silvey and Roach 1975; Holdren and Waltman 1984; van der Ploeg et al. 1992; van Breeman et al. 1992; Utkilen and Froshaug 1992; Izaguirre 1992; Rosen et al. 1992;

Seligman et al. 1992; Zisette et al. 1994; Blevens et al.1995; Jones and Korth 1995). Other odorous volatile organic compounds produced by natural freshwater algal blooms include alcohols, ketones, nor-carotenoids, hydrocarbons, organic sulfides, and amines (Soeder and Siegel 2000). However, in his review of tastes and odors in the aquatic environment, Wronowski (1992) noted that the relative contribution of actinomycete bacteria to taste and odor problems tended to be low, whereas the contributions of planktonic and benthic blue-green algae (cyanobacteria) in contrast tended to be very high.

A study that was performed on eutrophic Saginaw Bay, Lake Huron, by Bierman et al. (1984) provides the reader with an excellent practical example of the general type of relationship that can commonly be observed between blue-green algal growth and taste and odor problems in drinking water supplies. Bierman et al. (1984) observed a strong statistical correlation between threshold odor (TO) observed in the Saginaw-Midland (Michigan) municipal water supply and blue-green algal biomass (BG, mg dry weight per liter):

(1) $TO = 1.47\ BG + 2.04,\ r^2 = 0.534$

during the study period 1974-1980. The relationship between threshold odor and blue-green algal biomass in this study was found to be even stronger when a single 12-month period was considered (1974), thus removing some of the environmental noise due to interannual variability:

(2) $TO = 1.82\ BG + 1.86,\ r^2 = 0.713.$

The Saginaw Bay experience also provides an excellent example of a water quality restoration success story. Since the mid-1970s, phosphorus loading controls have been implemented in the Saginaw Bay watershed in an attempt to reduce the magnitude of algal blooms, adverse taste and odor problems, and filter clogging experienced at the Saginaw-Midland (Michigan) water treatment plant. These watershed-level phosphorus loading restrictions were very successful in reducing both spring total phosphorus concentrations and the biomass of blue-green algae in the inner bay. More importantly for consumers of the drinking water processed at this facility, the total number of days on which threshold odor exceeded the USPHS standard at this plant consequently decreased from 56 days in 1974 to 0 days in 1980.

This linkage between the nuisance growth of blue-green algae and the subsequent development of taste and odor problems in drinking water can be seen elsewhere in the U.S. as well. For example, Seligman et al. (1992) noted a strong correspondence between geosmin concentrations and concentrations of blue-green algae (*Anabaena*, *Aphanizomenon*, and *Oscillatoria*) in two northern California water supply reservoirs. Later studies of the San Leandro Reservoir (Merritt Smith Consulting 1999) confirmed that geosmin concentrations in the water were strongly correlated with the abundance of a small-celled species of *Anabaena*: the timing of peak geosmin concentrations corresponded closely with the peak in cell numbers of this blue-green algal species.

Merritt Smith Consulting (1999) proposed a recommended taste and odor control strategy for the San Leandro Reservoir that was composed of four major elements: hypolimnetic aeration, winter dilution, summer dilution, and optional extended mixing. However, the capital costs of implementing this strategy were estimated to be $1.2 million, and the overall life cycle cost was estimated to be $4.5 million.

Similarly, the city of St. Paul (Minnesota) derives drinking water from the Vadnais Lake Chain, which is fed mainly by diversions from the Mississippi River and runoff from local watersheds. In 1984, intensive lake and watershed studies were undertaken to identify the causes and remedies for frequent taste and odor episodes experienced by the St. Paul Water Utility during the late 1970s and early 1980s. Attempts to control these problems by adding chemicals at the water treatment plant (primarily powdered carbon and potassium permanganate), and by adding copper sulfate weekly to the supply lakes during the growing season to control blue-green algal growth were largely unsuccessful (Walker et al. 1989). Periods of fishy water (occurring largely in late spring or early summer, and periods of musty water (occurring generally in the late summer or early fall) prompted significant consumer complaints (Walker et al. 1989), and analyses of available water quality data by Walker (1985a) revealed that the three most severe taste and odor episodes were accompanied by blooms of blue-green algae, including Anabaena and *Aphanizomenon*. Nuisance algal blooms and a high risk of taste and odor problems occurred when chlorophyll concentrations in Vadnais lake exceeded 30 ug/L (Walker 1985b). Following three years of collecting baseline data, water quality control measures were implemented; these controls targeted supply sources of phosphorus, including diversions from the Mississippi River, runoff from urban watersheds, and recycling from lake bottom sediments. Walker et al. (1989) reported substantial success from these efforts in terms of reduced nutrient levels in the supply lakes, reductions in taste and odor problems, and cost savings of $300,000 per year associated with sharply reduced powdered carbon and potassium permanganate doses at the water treatment plant.

Taste and odor in other Kansas impoundments. In Kansas impoundments, taste and odor problems have been similarly found to be directly related to the reservoirs' trophic state, or nutrient enrichment status. For example, Arruda and Fromm (1989) made a comparative study of six water supply reservoirs in eastern Kansas: Alma City Lake, Lake Miola, Madison City Lake, Mound City Lake, Strowbridge Reservoir, and Yates Center Reservoir. These investigators made explicit measurements of odor, using a subjective human panel assessment procedure, and concluded that this relative surface water odor index was positively correlated with Carlson's (1977) trophic state index based on chlorophyll. The odor problems found in these six reservoirs were associated with the nuisance growth of a wide variety of algal species, including blue-green algae such as *Anabaena*. A plot of Arruda and Fromm's data is shown in Fig. 1.

A similar relationship between lake fertility and drinking water taste and odor problems has also been found in Clinton Reservoir, a eutrophic 31 km^2 water supply reservoir located near Lawrence, Kansas. DeNoyelles (2000) noted that very high concentrations of geosmin occurred in fall 1997, and that the highest concentrations of geosmin were generally found in the transitional and basin sites where the abundance of cyanobacteria was greatest. Data from Clinton Reservoir (deNoyelles et al. 1999) were thus re-analyzed to explore possible relationships between measured geosmin concentrations and quantitative measurements of water quality. When the data from all 12 sampling stations in this reservoir were plotted, a strong positive correlation was found between November geosmin levels and May-November mean concentrations of chlorophyll in the water column at the nine transitional and mainstem sites (Fig. 2). Only the three riverine sites (in which the phytoplankton is influenced primarily by flow and other riverine processes, and has not yet had time to experience the more stable water column conditions characteristic of the reservoir proper) did not appear to fit the overall trend.

The relationship shown for Clinton Reservoir in Fig. 2 confirms the general trend observed by Arruda and Fromm (1989), and indicates that water quality management practices that are explicitly designed to reduce algal growth should help to minimize the likelihood of future taste and odor problems in Kansas water supply reservoirs. Wang et al. (1999) concluded that controlling the abundance of blue-green algae in Clinton Reservoir may be necessary to alleviate taste and odor problems associated with geosmin production in this waterbody, and suggested enacting watershed management practices to decrease the magnitude of phosphorus loading to the lake. These studies of Kansas impoundments thus strongly suggest that the taste and odor problems observed in eutrophic Cheney Reservoir are likely to be linked causally to excess nutrient loading from the watershed, and to the subsequent growth of taste and odor-producing organisms such as blue-green algae and actinomycete bacteria.

The September 1994-September 1995 mean concentration of chlorophyll in Cheney Reservoir (15 ug/L) measured by the U.S. Fish and Wildlife Service (1996) is in fact at the upper end of the mean chlorophyll values observed in six eastern Kansas reservoirs that exhibited significant odor problems (range = 3.1-16.6 ug/L; see Table 2 in Arruda and Fromm 1989). Unfortunately, measurements of past phytoplankton abundance and species composition typically are not available for Cheney Reservoir, with the possible exception of past KDHE sampling surveys.

However, the eutrophic condition of Cheney Reservoir makes it very likely that nuisance blue-green algal blooms can occur in this impoundment. In particular, the mean total nitrogen:total phosphorus ratios reported for the water column (TN:TP = 6.45 by mass) and the outflow (TN:TP = 5.62 by mass) reported by the U.S. Fish and Wildlife Service (1996) for Cheney Reservoir are extremely low. As noted by the U.S.F.W.S. report, TN:TP ratios are much lower than the empirical TN:TP ratio threshold of ,29:1 found by Smith (1983) to favor blue-green algal blooms. The phytoplankton of Cheney Reservoir would therefore be expected to have a high probability of being dominated at least periodically during the year by the blue-green algal species that capable of causing taste and odor problems. An assessment of the spatial and temporal variability of algal species composition in Cheney Reservoir to test this hypothesis was a major goal of our study.

Potential applications of existing eutrophication modeling frameworks to Cheney Reservoir. Predictive models for the management of eutrophication and its symptoms have been developed and tested extensively during the past 25 years (Vollenweider 1968; OECD 1980; Reckhow and Chapra 1983; Cooke et al. 1993). This quantitative framework has been applied with marked success in lakes and reservoirs worldwide (Smith 1998; Smith et al. 1999), and it forms the conceptual and practical basis for the water quality study presented here. In essence, this framework relates a Water Quality Variable of Concern (here identified by the City of Wichita Water and Sewer Department as taste and odor problems in the drinking water, which can be monitored by measuring dissolved concentrations of geosmin and MIB) to measured values of key limnological variables that can be manipulated by in-lake or external water quality management methods.

The empirical method that has been used successfully worldwide in eutrophication management (Fig. 3) contains the following general steps:

1. *Develop a quantitative relationship between the Quality Variable of Concern (identified here as taste and odor, as indicated by concentrations of geosmin and MIB in the water) and a key limnological variable that can be controlled (e.g. algal biomass, as indicated by concentrations of chlorophyll a, the primary photosynthesis pigment in algae).* The data from seven other Kansas reservoirs in Figures 1 and 2 suggested to us that it was highly probable that a strong relationship exists in Cheney Reservoir between geosmin (and MIB) and chlorophyll concentrations. However, in the study reported here we also measured and examined other potentially important limnological factors, such as algal species composition and actinomycete abundance, that could modify or improve this relationship.

2. *Develop quantitive relationships between this key limnological variable (e.g., chlorophyll a, ug/L) to concentrations of total phosphorus in the water body (TP, ug/L).* Phosphorus is the most common nutrient that limits algal growth and biomass in lakes and reservoirs (OECD 1982; Cooke et al. 1993; Smith 1998), and is the nutrient that is most easily controlled by both external and internal loading controls.

3. *Develop quantitive relationships between total phosphorus concentrations (TP, ug/L) and levels of external phosphorus loading to the lake (J_p, kg P/yr).* This latter relationship allows managers to link reservoir water quality directly to both point and non-point nutrient sources in the watershed that potentially can be controlled or restricted.

This procedure is used as follows (see Fig. 3): if a critical value of geosmin is stipulated (that is, a critical value of geosmin is established beyond which significant taste and odor problems occur in the City of Wichita water supply system), then this critical value can be used to calculate the acceptable phosphorus loading limits for Cheney Reservoir that will be needed to minimize the possibility that the critical geosmin value is exceeded. For example, the concentration of geosmin that can be detected by people sensitive to smell ranges from 4 nanograms per liter (Zizette et al. 1994) to 10 ng/L (Wnorowski 1992), and an operational critical value for geosmin of 5 ng/L can reasonable be proposed. This proposed critical value is shown as an asterisk in Fig 3.1. Once this critical value has been defined, a lake manager can in turn apply relationships 1 through 3 in sequence to calculate permissible phosphorus loading rates for the lake: the graphical estimate of this permissible loading rate is shown by two asterisks in Fig. 3.3. Such permissible phosphorus loading rates could then be used as targets to attain, and water quality managers can then evaluate the specific watershed nutrient control practices that needed to be implemented in order to achieve the targeted loading value.

We did not attempt to fully develop relationships 3.1-3.3 in the current study, because such a task is highly complex, demands more extensive resources and personnel, and is best implemented in carefully designed stages or phases. We instead performed a 14 month survey of the physical, chemical, and biological characteristics of Cheney Reservoir. The intent of this water quality assessment was to collect the essential data needed to develop predictive relationships between taste and odor and water quality measurements, as required by the general eutrophication modeling procedure outlined above.

Goals of this Study

As in a similar water quality study of Clinton Reservoir (deNoyelles et al. 1999), the goals of this study included the following:

1. Acquire, review, and analyze physical, chemical, and biological data on Cheney Reservoir;
2. Determine through new field studies the temporal and spatial extent, and the nature of, important water quality characteristics of the reservoir;
3. Assess the current trophic status of the reservoir;
4. Monitor and evaluate phytoplankton community structure and its potential impact on water quality in the reservoir;
5. Evaluate actinomycete abundance relative to reservoir water quality;
6. Make explicit measurements of the odor-producing compounds geosmin and MIB, and relate these observed geosmin and MIB levels to key physical, chemical, and biological characteristics of the reservoir.
7. In collaboration with personnel from the City of Wichita Water and Sewer Department, attempt to develop provisional water quality management strategies for Cheney Reservoir that will help to minimize eutrophication and the intensity and extent of taste and odor problems. These strategies might involve external nutrient controls, within-reservoir algal and nutrient control procedures, or both (cf. Cooke et al. 1993).

Approach and Methods

A monthly sampling program for Cheney Reservoir was begun in August 1999, and continued through October 2000. Six permanent sampling stations were monitored once monthly during this period, with additional samples taken on an ad hoc basis during periods in which reports of taste and odor problems were relayed by the public to the Wichita Water and Sewer Department. These six stations were arrayed along the length of Cheney Reservoir in order to capture in our sampling the linear gradients of water chemistry and algal biomass that can occur along the length of artificial impoundments (Thornton et al. 1982; Perkins and Underwood 2000), with the first sampling station located near the dam and the sixth station located upstream in the most riverine region of the reservoir. In addition to this sampling schedule, additional samples were taken by Wichita Water and Sewer Department staff in response to taste and odor complaints made by the public; these samples were sent directly to the PI's laboratory for analyses of geosmin, MIB, total nitrogen, total phosphorus, and phytoplankton species composition.

The six permanent sampling stations are shown as solid circles in Fig. 4, and include three of the fourteen locations sampled by the U.S. Fish and Wildlife Service (1996). The field component of this project was coordinated by F. deNoyelles, who participated in sampling and helped to train and supervise the field crew. The field crew was comprised of Jonathan Sieber-Denlinger, the PI's technician, and Scott Campbell, an employee of the Kansas Biological Survey. Additional assistance was periodically provided by Andy Dzialowski, a graduate student in the PI's laboratory. All permanent sampling stations were located using global positioning system (GPS) techniques, using a Magellan GPS unit.

On each sampling date, standard limnological measurements were used to evaluate water quality at each of the six permanent stations. These measurements included Secchi disk transparency, using a 20 cm white Secchi disk; vertical profiles of temperature, dissolved oxygen, pH, turbidity, conductivity, and chlorophyll fluorescence; and vertical profiles of underwater light extinction. The vertical profiles of water chemistry were performed using a YSI 6600 multiprobe and YSI 610DM meter, which was calibrated according to the manufacturer's instructions prior to each sampling event. Underwater light extinction was measured using a Li-Cor model LI-250 quantum radiometer and spherical quantum sensor.

Integrated water samples were also taken on each sampling date for later measurements of water chemistry and extracted chlorophyll *a*, and for microscopical phytoplankton analyses. At each site, a large (>2 liter) integrated sample was taken by lowering a weighted Tygon hose into the water column down to a depth of 2 meters. The contents of the hose were then be drained into a small carboy and mixed thoroughly. One 500 mL subsample from the carboy was then poured into an opaque, acid-washed bottle and retained on ice for later measurements of total phosphorus, soluble reactive phosphorus, nitrate, nitrite, and ammonia. Initially, several of these chemical measurements were provided by the City of Wichita Water and Sewer Department laboratories, and were overseen by the Laboratory and Operations Director, Terryl Pajor; copies of these data will be generously provided to the PI in Lawrence. Several months into the study, all chemical analyses were performed in the laboratory of the PI.

An additional 100 mL sample was poured into an opaque glass bottle and preserved with 1 mL of acid Lugol's solution for later phytoplankton identification and enumeration, which was made for the dominant phytoplankton species by Scott Campbell following training by Dr. Jerry deNoyelles. A further subsample for actinomycete bacteria detection and enumeration was collected according to Standard Methods section 9060A (APHA 1998). A 1L sample was poured into a teflon-lined bottle for later measurements of geosmin and MIB, TOC, and DOC. These measurements were performed in the laboratory of Steve Randtke.

The remaining water from the integrated sampler was poured into an opaque, acid-washed bottle brown plastic bottle, capped tightly, and retained on ice in a cooler for later measurements of total nitrogen, extracted chlorophyll *a*, geosmin and MIB, and actinomycete enumeration in Lawrence. Total nitrogen was measured using ultraviolet spectrophotometry after alkaline persulfate digestion (reference). Extracted chlorophyll *a* (a direct measurement of total phytoplankton biomass) was measured by filtering 250-500 mL of lakewater through a Whatman GF/F glass fiber filter. The particulate chlorophyll retained by the filter was then extracted in ethanol and measured fluorometrically using a Quantech digital fluorometer, following Standard Methods section 10200H (APHA 1998). This fluorometer was calibrated frequently using liquid chlorophyll *a* standards purchased from Quantech. Measurements of dissolved inorganic phosphorus, ammonia, and nitrate-nitrogen were then performed on the GF/F filtrates using standard spectrophotometric methods.

Geosmin and MIB were measured on the 1L subsamples using a GC/MS on selected ion mode; this analytical method had already been established and calibrated in his laboratory. The detection and enumeration of actinomycetes were initiated within 1 day after sampling, using plating methods outlined in Standards Methods section 9250A and 9250B (APHA 1998). These analyses were be overseen by Dr. David Graham, and were performed with the assistance of his graduate students. As noted in the first Quarterly Report, Chuck Lander left KU for the University of Illinois soon after this study began, and Hyung Kim took over the actinomycete measurements. As a result, two different personnel produced these data, and as will be seen below, the initial data collected by Mr. Lander appear to be inconsistent with those collected later.

Results and Discussion

Initial verification and assessment of analytical methods. Concurrent measurements of total phosphorus by our lab and by the City of Wichita Water and Sewer Department in August 1999 allowed us to perform a cross-validation of our analytical methods, and this analysis (Table 1) revealed no significant difference between these two sets of results (2-tailed T test, $P>0.1$). We thus are very confident in our analyses of phosphorus in this study.

Table 1. Comparison of TP measurements from Wichita and KU.

t-Test: Paired Means

	Wichita TP	KU TP
Mean	120.8333	129.8917
Variance	1171.97	461.0282
Observations	12	12
Pearson Correlation	0.88349	
Hypothesized Mean Difference	0	
Degrees of Freedom	11	
tStatistic	-1.71656	
P(T<=t) one-tail	0.057024	NS
TCritical, one-tail test	1.795884	
P(T<=t) two-tail	0.114049	NS
tCritical, two-tail test	2.200986	

As noted in Quarterly Report 1, measurements of the photosynthetic pigment chlorophyll *a* provide a commonly accepted method for estimating the concentration of algal biomass in freshwater lakes and reservoir. In this study we used both spectrophotometric and fluorometric methods in the laboratory to analyze chlorophyll *a*, and also made field measurements of chlorophyll fluorescence with our YSI multiprobe. However, during the course of the project we concluded that spectrophotometry was the most reliable and least variable method for chlorophyll *a* anyalysis (see Quarterly Report 4), and only standard spectrophotometric chlorophyll a measurements were utilized in all of the graphical and statistical analyses below.

Trophic state and average limnological properties of Cheney Reservoir. As reported by the U.S. Fish and Wildlife Service (1996), *in situ* profiles of temperature and conductivity indicate that Cheney Reservoir does not exhibit strong thermal stratification during the summer (data not shown). This reservoir is highly mixed by the wind, and only very weak thermal gradients were observed at any time during the 14 month sampling period from August 1999 until October 2000.

The mean values for each primary limnological parameter measured in this study at each of the six permanent sampling stations are summarized in Table 2. As can be seen in Table 3 below, the surface sample data collected by the U.S. Fish and Wildlife Service (1996) compare very favorably with these values. Both sets of data confirm that Cheney Reservoir is nutrient enriched, and highly productive.

Table 3. Summary of September 1994-September 1995 means of major limnological parameters for Cheney Reservoir (from U.S. Fish and Wildlife Service 1996, Table 2).

Turbidity	PH	Conductivity	NH_3-N	NO_3-N	TN	TP	TN:TP	TOC	Chl a
NTU		uS cm-1	ugN/L	ugN/L	mgN/L	ugP/L		ugC/L	ug/L
30	8.4	802	111	187	0.871	135	6.45	5861	15

Nutrient-chlorophyll relationships in Cheney Reservoir. Spectrophotometric measurements of the photosynthetic pigment chlorophyll *a* have provided us with quantitative estimates of total algal biomass in Cheney Reservoir. As can be seen in Fig. 5, the mean concentrations of chlorophyll *a* tended to covary with concentrations of total phosphorus at the six permanent sampling stations. A similar analysis with total nitrogen revealed a non-significant relationship (Fig. 6), and the suggestion of a positive correlation was due primarily to the presence of one data point (Station 6).

Comparisons with other reservoirs. We also used the data from our six sampling stations to assess the degree to which algal biomass in Cheney Reservoir, and in lakes and reservoirs from nearby Missouri, responded similarly to nutrients. As can be seen in Fig. 7, *the mean concentrations of cholorphyll at sites 1-6 in Cheney Reservoir were found to fall markedly below the long-term phosphorus-chlorophyll relationship reported for Missouri waterbodies by Jones and Knowlton (1993), suggesting that the yield of chlorophyll per unit total phosphorus is much lower in Cheney Reservoir than for the vast majority of Missouri water bodies*. This unexpected difference in the algal response to nutrients in Cheney Reservoir was somewhat surprising, but it may be due to the presence of high non-algal turbidity due to elevated concentrations of non-algal seston.

Light, nutrients, and limiting factors in Cheney Reservoir. Turbidity caused by the presence of non-algal seston (NAS, mg/L) from suspended clay or organic matter is strongly regional, and depends upon the local soil characteristics, vegetation, and hydrology. The presence of such non-algal turbidity can produce low algal chlorophyll-to-nutrient ratios, and can result in a lack of correlation between chlorophyll a and total phosphorus in some waterbodies (Gibson et al. 2000). NAS most likely affects phytoplankton by reducing underwater light availability, and consequently reducing algal growth and nutrient demand (Hoyer and Jones 1983; Knowlton and Jones 2000). We investigated this possibility in Cheney Reservoir in the two sets of analyses reported below.

In lakes and reservoirs having low to negligible concentrations of non-algal seston, a strong inverse relationship is typically found between concentrations of chlorophyll *a* (chl *a*, ug/L) and Secchi disk transparency (SD, m) because the pigmented phytoplankton cells strongly attenuate downwelling light energy in the water column. An inverse chlorophyll *a* - Secchi disk relationship was found in Cheney Reservoir (Fig. 8), with the lowest concentrations of chlorophyll and greatest transparency occurring near the dam.

(3) $SD = -0.289 \text{ chl } a + 27.6, r^2 = 0.75,$

suggesting that algal cells were contributing to vertical light extinction in this waterbody.

A relatively strong positive correlation was indeed observed between mean concentrations of chlorophyll a and the mean vertical extinction coefficient for light (K, m^{-1}) at the six permanent sampling stations (Fig. 9), confirming that algal growth contributed significantly to light attenuation in Cheney Reservoir.

(4) $K = 0.14 \text{ chl } a + 1.20, r^2 = 0.75$

However, much stronger statistical relationships were observed when nephelometric turbidity (NTU) replaced chlorophyll a as the independent variable in these regression analyses (Fig. 10, 11):

(5) $SD = -1.23 \text{ Turbidity} + 100.9, r^2 = 0.95$

(6) $K = 0.063 \text{ Turbidity} + 0.50, r^2 = 0.90$

Nephelometric turbidity measures not only the magnitude of light attenuation by algal cells, but also turbidity causes by the presence of other non-algal particulates such as suspended soils. The much stronger relationships Fig. 10 and 11 suggest that non-algal seston contributes significantly to light extinction, and may be having a significant inhibitory effect on the production of phytoplankton in Cheney Reservoir.

In order to test this hypothesis further, we compared our data for Cheney Reservoir to data in Carney's (2001) recent comparative study of water quality in 35 Kansas waterbodies. We calculated our own values for each of the six water quality metrics presented by Carney (2001), who analyzed single samples from Cheney Reservoir as well as 34 other Kansas reservoirs in mid-summer 1999. Table 4 below summarizes both the KDHE values obtained by Cheney Reservoir in July 1999 just prior to the initiation of our own sampling, and 14-month means from our longer-term survey. KDHE-calculated values of each of these six metrics for Cheney Reservoir in July 1999 (Table 4, top line) are very similar to the values that we obtained during our sampling program (Table 4, bottom section).

Table 4. Limiting factor determinations in Cheney Reservoir.

Site	TN:TN	NAT	Z_{mix}*NAT	Chl-a*SD	Chl-a/TP	Z_{mix}/SD	Shading
Cheney	5.2	1.89	8.98	2.99	0.05	9.70	9.74

Our data:

site	TN/TP	NAT	Zmix*NAT	Chl-a*SD	Chl-a/TP	Zmix/SD	Shading
site 1	6.0	1.31	15.52	5.672	0.079	18.08	28.50
site 2	5.4	1.65	9.82	5.476	0.086	11.38	17.68
site 3	6.2	1.33	11.70	6.472	0.094	13.96	21.34
site 4	6.0	1.53	11.96	6.000	0.097	14.07	20.64
site 5	6.1	1.48	8.62	6.783	0.106	10.38	17.23
site 6	5.0	1.82	5.55	7.153	0.127	6.76	10.41
mean	**5.8**	**1.52**	**10.53**	**6.26**	**0.098**	**12.44**	**19.30**

Key:

1. Non-Algal light extinction due to turbidity, **NAT**
   (=(1/SD)-(0.025m2/mg * Chl-a))
2. Light availability in mixed layer = **Zmix*NAT** (=mean depth of site * NAT)
3. Partitioning of light extinction between algae and non-algal turbidity = **Chl-a*SD**
   (=chlorophyll-a in mg/m3 * Secchi disk transparency)
4. Algal use of phosphorus supply = **Chl-a/TP**
   (=chlorophyll-a in mg/m3 / TP)
5. Light availability in the mixed layer for a given surface light = **Zmix/SD**
   (=mean depth of site / Secchi disk transparency)
6. Shading in water column due to algae and inorganic turbidity = **Zmean*K**
   (=mean depth of site* light extinction coefficient)

Interpretation:

1. Values >1.0 indicate that inorganic particles are important in creating turbidity.
2. Values >6.0 indicate very low light availability for algal growth.
3. Values <=6.0 indicate that inorganic turbidity dominates light extinction.
4. Values <0.13 indicate a low algal response to phosphorus, suggesting that nitrogen, light, or other factors are important.
5. Values >6.0 indicate that light availability is low and algal responses to nutrients are low.
6. Values >16 indicate high levels of shading due to the presence of algae and/or inorganic particles.

Interestingly, long-term (August 1999-October 2000) mean values for the total nitrogen:total phosphorus ratio (TN:TP), indicate strong potential N-limitation of algal growth in Cheney Reservoir. As can be seen in Fig. 7 above, Cheney Reservoir also behaves very similarly in its phosphorus-chlorophyll relationship to Missouri reservoirs having TN:TP ratios less than 10:1 by mass, a ratio that is an empirical indicator of potential growth limitation by nitrogen (Smith 1982).

However, the lack of a strong correlation between chlorophyll and TN in Fig. 6, and several of the metrics presented above in Table 4, suggest the presence of strong light-limitation of algal growth in Cheney Reservoir that may strongly modify or amplify the effects of N-limitation on algal growth. For example, estimates of non-algal turbidity (NAT, m^{-1}) are high, and estimated light availability in mixed layer (Zmix*NAT) is low (Table 4). The third metric, which estimates the partitioning of light extinction between algae and non-algal turbidity (chl a*SD), also suggests that inorganic turbidity dominates light extinction in Cheney Reservoir. Despite the high availabilities of plant nutrients (as measured here as concentrations of total phosphorus and total nitrogen), *we thus conclude that phytoplankton biomass in Cheney Reservoir is likely to be strongly depressed by shading due to non-algal seston (NAS) present in the water column, accounting at least in part for the deviation of Cheney Reservoir from the typical phosphorus-chlorophyll pattern seen in Fig. 7.*

Phytoplankton species composition. As stressed by Smith (1993) and Smith and Bennett (1999), nitrogen limitation favors the proliferation of blue-green algae over other more desirable algal species. Carney's (2001) report allowed us to make a direct comparison of the phytoplankton species composition in Cheney Reservoir with that of the 35 other reservoirs that he studied in 1999. As can be seen in Fig. 12, the relationship between total algal biomass and % blue-green algae in Kansas impoundments studied in this brief survey was very strongly curvilinear, and near-monocultures of blue-green algae occurred in many of the most nutrient-enriched waterbodies sampled. Surprisingly, however, the phytoplankton community in Cheney Reservoir contained only 7% blue-green algae by biovolume when it was sampled by the KDHE in July 1999, even though many other Kansas reservoirs of very similar fertility exhibited much greater dominance by cyanobacteria.

We examined this question further using our own phytoplankton analyses, which indicated a pattern of strong diatom growth at all six permanent sampling stations in Cheney Reservoir throughout much of the year. The most common algal species observed on the majority of our sampling dates were the centric diatoms *Cyclotella* (Fig. 13) and *Melosira* (Fig. 14), both of which are highly edible by aquatic grazers, and are a high quality food for herbivorous zooplankton. However, beginning in mid-July (around Julian Day 200), pronounced blooms of the nitrogen-fixing blue-green algae *Anabaena* and Aphanizomenon appeared in Cheney Reservoir. As can be seen in Fig. 15 and 16, these blue-green blooms produced biomass values far in excess of the spring *Cyclotella* bloom in early March near Julian Day 70. This seasonal occurrence of nitrogen-fixing blue-green algae in Cheney Reservoir was consistent with the hypothesis that low TN:TP ratios typically favor the growth of nuisance blue-greens over other phytoplankton species (Smith 1983; Smith and Bennett 1999). Much smaller growths of a third nuisance blue-green alga, *Microcystis*, were also observed during the summer months. As will be seen below, these data are very important, and we attribute much of the observed variation in taste and odor in Cheney Reservoir to the growth of blue-green algae.

Taste and odor compounds in Cheney Reservoir. The most important goal of this study was to examine the patterns of MIB and geosmin production in Cheney Reservoir, and to assess which biological, chemical, and physical factors are most likely to contribute to taste and odor production in the lake. These analyses are summarized below.

Concentrations of geosmin and MIB. As noted in our five quarterly reports, the primary taste and odor-causing organic compounds geosmin and MIB were typically present only at low to undetectable levels during the 14 month study period. Methyl isoborneol (MIB) in particular was never present at elevated levels, and typically never exceeded a concentration of 2 ng/L. Wnorowski (1992) reports that the threshold odor concentration for MIB is ca. 29 ng/L, and we thus tentatively conclude that during the period of study reported here, MIB was unlikely to be a major causal agent for taste and odor problems in the City of Wichita's drinking water supply. Geosmin concentrations in Cheney Reservoir in contrast were much more variable than MIB, and the mean geosmin concentrations exceeded the human detection limit (5 ng/L) at four of the six sampling stations during the study period. However, the mean geosmin concentrations observed in Cheney Reservoir were typically very modest (Table 2 above).

In contrast, recent of water quality studies of Clinton Reservoir have revealed consistently high levels of geosmin (deNoyelles et al. 1999; Wang et al. 1999). For example, concentrations of geosmin in Clinton Reservoir in fall and winter 1997 were very high (up to 170 ng/L). In fall and winter 1995/1996, even higher geosmin concentrations (ca. 200 ng/L) caused the West Lawrence drinking water treatment plant's operation to be suspended for 8 weeks between December 1995 and January 1996.

Why should there be such profound differences in taste and odor production in these two impoundments? As stressed in our fourth Quarterly Report, the principal working hypothesis of our study is that *geosmin and subsequent taste and odor problems in Cheney Reservoir originate primarily from the biological activities of one or more species of phytoplankton algae.* As has been shown in Fig. 2, peak geosmin concentrations measured in November tended to be positively correlated in Clinton Reservoir with total algal biomass during the previous six month period, as estimated by May-October mean concentrations of chlorophyll *a*. Similarly, mean concentrations of geosmin in Cheney Reservoir tended to be positively correlated with mean concentrations of chlorophyll *a* at each of our six permanent sampling stations (Fig. 17), and an analogous plot of mean geosmin vs mean total phosphorus concentrations is shown in Fig. 18. These three empirical relationships are consistent with the hypothesis that geosmin production in Kansas reservoirs is driven either by total algal production, or by the abundance of some component of the algal community (e.g., blue-green algae).

We tested the latter hypothesis directly by making a plot of the observed peak concentrations of geosmin (which were measured in November 1995) in Clinton

Reservoir versus the May-December mean total biomass of cyanobacteria. We then overlaid upon these data a plot of the peak concentrations of geosmin (typically observed in July 2000) versus the 14-month mean total biomass of cyanobacteria in Cheney Reservoir. As can be seen in Fig. 19, there is a strong positive correlation between mean blue-green algal biomass and peak geosmin concentrations in both of these two drinking water supply reservoirs, and both responses appear to be very similar.

Based upon the data shown in Fig. 19, we tentatively conclude that taste and odor problems in the water supply to the City of Wichita primarily result from the growth of blue-green algae. In addition, we conclude that the very low frequency of a taste and odor problems in the City of Wichita water supply results from a reduced growth of blue-green algae in Cheney Reservoir, relative to that observed in equally eutrophic Clinton Reservoir. The causes of lower blue-green algal growth in Cheney Reservoir are not yet fully understood, but as appears to be true for chlorophyll *a* (see Fig. 7), these lower levels of nuisance cyanobacterial biomass are likely to be due to the presence of high concentrations of suspended soils. Smith (1990) has previously documented strong inhibitory effects of suspended soils in an analysis of blue-green algal growth in turbid North Carolina Reservoirs.

Supporting data from individual taste and odor events. Dr. Jerry deNoyelles and Scott Campbell also analyzed the additional water samples taken during the taste and odor event that occurred from 9-14 March 2000 during the reservoir drawdown, as well as later sampling dates in mid-July 2000. Their analyses have helped us further to evaluate the potential role of algal blooms in causing periodic taste and odor events in Cheney Reservoir. As can be seen in Fig. 13, the brief taste and odor event in spring 2000 likely coincided with the short-lived spring bloom of the diatom *Cyclotella*. However, the later event in mid-summer almost certainly corresponded to the more extended nuisance growth of blue-green algae such as *Anabaena, Aphanizomenon, and Microcystis*.

Growth of Actinomycetes. Because Actinomycete bacteria also may contribute to taste and odor problems, David Graham and his graduate students made independent measurements of bacterial numbers in Cheney Reservoir throughout the study. Generally poor relationships were observed between mean Actinomycete abundance and mean concentrations of chlorophyll *a* over the entire study period (Fig. 20), and between mean geosmin concentrations and mean Actinomycete abundance (Fig. 21). However, as noted in our first Quarterly Report, we experienced significant initial difficulties with these enumeration methods, and the first graduate student in charge of these analyses left the University of Kansas to pursue graduate study elsewhere. When Hyung Kim continued these analyses, we observed a pronounced drop in the apparent abundance of Actinomycetes in the lake; we conclude that the initial data collected prior to his analyses were in error, and that only the data from March-October 2000 are legitimate. Although no correlation between Actinomycetes and mean chlorophyll was evident for this time period (Fig. 22), a weak relationship was nonetheless evident between mean geosmin concentrations and mean Actinomycete abundance in Cheney Reservoir (Fig. 23). However, because of the analytical problems that we have experienced, and because the current management frameworks for eutrophication control focus upon controlling the growth of phytoplankton, we only note the potential contributing role of Actinomycetes here, and do not use these data to develop management recommendations for Cheney Reservoir.

Attenuation of geosmin in water. Once produced biologically, geosmin and MIB concentrations in freshwaters tend to decrease over time due to natural attenuation processes. Shugen Pan, a graduate student with Steve Randtke, has performed a series of experiments to follow this attenuation process, and highlights directly related to Cheney Reservoir from his Ph.D. studies of this phenomenon are summarized below.

In a series of flask experiments performed in the laboratory, Pan (2001) found that concentrations of geosmin and MIB were found to be significantly degraded by natural microbial consortia, but the rates of biodegradation varied both among waters taken from different sources and among samples taken at different times of the year. The patterns of geosmin and MIB biodegradation in water from Clinton Reservoir, Cheney Reservoir, Reservoir #2 at the Nelson Environmental Studies Area (University of Kansas) are shown in Fig. 23-24 for samples taken on 25 February 2000, and in Fig. 25-26 for samples taken 12 June 2000. As can be seen in these four figures, the degradation of geosmin in particular was quite rapid, with 75-95% loss occurring over an interval of only 8 days. These studies suggest that in natural systems, concentrations of geosmin and MIB should be very labile and dynamic, with rapid biodegradation occurring within days of their liberation into the water column by algae and/or actinomycetes.

Implications of this work. The literature on non-point source pollution from agricultural watersheds is vast, and will not be reviewed here. However, agricultural activities are a very significant source of nitrogen and phosphorus to receiving waters (Carpenter et al. 1998), and production agriculture remains a major diffuse source of water pollutants and water quality degradation in the U.S. (Brezonik et al. 1999). It is now firmly established in the literature that algal growth in impoundments is strongly dependent upon their nutrient supplies (e.g., Jones and Knowlton 1993), and solutions to the problem of taste and odor in the water supply of the City of Wichita are likely best undertaken by finding ways to improve the quality of the water entering the reservoir from its watershed (Blain 2001). As noted by Blain (2001), a series of Best Management Practices (BMP's) have already been initiated in the Cheney Reservoir watershed, and a cost-sharing policy has been established between the City of Wichita and local producers in an attempt to help created these improvements.

As noted in the Introduction, a major goal of this study was to assist personnel from the City of Wichita Water and Sewer Department in developing provisional water quality management strategies for Cheney Reservoir that will help to minimize eutrophication and the intensity and extent of taste and odor problems. The data summarized in this report strongly suggest that taste and odor problems (as measured by concentrations of geosmin and MIB in the water column) are linked to algal growth in Cheney Reservoir, and in particular to the growth of cyanobacteria, or blue-green algae. We suggest here that watershed-level nutrient loading controls that are designed to minimize total algal biomass at all sites in Cheney Reservoir may be most effective management tool to limit the frequency and likelihood of taste and odor events in Cheney Reservoir, because the biomass of all potential taste and odor-forming species of phytoplankton (including blue-green algae) will be maintained at the lowest possible levels. In addition, future efforts to understand the ecological mechanisms leading to diatom dominance over blue-green algae in Cheney Reservoir will contribute not only to effective water quality management for this drinking water supply, but also will contribute significantly to our ability to predict and manage geosmin-related taste and odor problems in other Kansas impoundments. Experiments funded by no-cost extension to this project are currently in progress to examine the effects of nitrogen:phosphorus ratios on water quality in Kansas waters, because low nitrogen:phosphorus (N:P) ratios not only favor dominance by nuisance blue-green algae (Smith 1983), but low N:P ratios also favor enhance geosmin synthesis by cells of *Anabaena* (Saadoun et al. 2001).

What conceptual or quantitative frameworks can be used to help guide the future development and implementation of BMP's in the Cheney Reservoir watershed to help minimize those algal blooms and taste and odor problems? What procedures can be used to evaluate which BMP's are most cost effective, and which BMP's are most effective in restricting the actual flux of nutrients from the watershed into the reservoir itself? Brezonik et al. (1999) have presented an eight-step framework for the restoration and management of agricultural watershed, and other authors (Toombs 1997; Mankin et al. 1999; Thornton et al. 1999) have presented agricultural pollution control and integrated approaches to reservoir water quality modeling. Mankin et al. (1999) in particular have linked a watershed model (AGNPS) to a spreadsheet eutrophication model (EUTROMOD) in order to compare the predicted effects of a variety of watershed management scenarios on water quality in Melvern Lake, a 28 km^2 multipurpose reservoir in central Kansas. Lathrop et al. (1998) have used a phosphorus mass balance model to calculate the phosphorus loading reductions needed to control blue-green algal blooms in eutrophic Lake Mendota (Wisconsin), where both agricultural and urban runoff from its watershed have maintained a high fertility in the lake water. In the highly agricultural watershed of Lake Simcoe (Ontario, Canada), cost-sharing programs have been in place since the 1980s to reduce agricultural loading to the lake, and over 300 remediation projects have reduced phosphorus loadings by an estimated 7.5 million metric tons per year (Toombs 1997).

We believe that the examples provided by Bierman et al. (1984), Walker et al. (1989), and Lathrop et al. (1998) indicate that phosphorus loading restrictions provide a logical and scientifically defensible approach to the control of taste and odor problems associated with nuisance blue-green algal growth in municipal water supplies. In this study we have developed a series of empirical relationships that relate concentrations of geosmin to blue-green algal biomass (Fig. 15), to concentrations of chlorophyll a (Fig. 17), and to concentrations of total phosphorus.

The data presented in Fig. 17-18 further suggest that efforts to maintain mean total phosphorus concentrations below 110 ugP/L, and mean chlorophyll a concentrations below 11 ug/L, at all sites in the waterbody should maintain mean geosmin concentrations below the limit of human detection (5 ng/L) in drinking water obtained from Cheney Reservoir. Following the conceptual framework illustrated in Fig. 3, we suggest that empirical nutrient loading models such as those presented by Canfield and Bachmann (1981) and in Mankin et al. (1999) can in turn be used to establish the target phosphorus loadings needed to maintain total phosphorus concentrations in Cheney at or below this proposed critical level (110 ug P/L). Objective methods such as those used by Mankin et al. (1999) can then potentially be used to evaluate the effectiveness of BMP's designed to reduce phosphorus loading from the watershed to these target values.

Conclusions

1. Cheney Reservoir is highly nutrient-enriched due to extensive nutrient loading from its watershed, as evidenced by high concentrations of total nitrogen, total phosphorus, and algal biomass (as indicated by concentrations of the plant pigment chlorophyll *a*). These conclusions are consistent with past water quality assessments made by the U.S. Fish and Wildlife Service (1996) and by Carney (2001).

2. The yield of chlorophyll a per unit total phosphorus in Cheney Reservoir is unusually low, as evidenced by a direct graphical comparison with a long term database from lakes and reservoirs in Missouri collected by Jones and Knowlton (1993).

3. Although total nitrogen:total phosphorus ratios <10:1 by mass in Cheney Reservoir suggest the possibility of nitrogen limitation, analyses of underwater light and transparency data suggest that high concentrations of non-algal seston (suspended soils) may sharply reduce light availability and may contribute to strong light-limitation of algal productivity in the reservoir. Such light limitation is a likely to be a primary contributor to the reduced yield of chlorophyll *a* per unit total phosphorus that is observed in Cheney Reservoir.

4. Total nitrogen:total phosphorus ratios <10:1 by mass in Cheney Reservoir suggest the possibility of strong cyanobacterial dominance, and analyses of phytoplankton data from this study confirm that blue-green algae dominate the mid- and late-summer biomass of phytoplankton at the six permanent stations sampled here.

5. Empirical correlations between measured concentrations of geosmin and total blue-green algal biomass in Cheney Reservoir support the hypothesis that taste and odor problems in this drinking supply are causally linked to the growth of blue-green algae.

6. We conclude that the low values of geosmin typically observed in Cheney Reservoir result primarily from the fact that the phytoplankton of this impoundment is typically less dominated by blue-green algae (cyanobacteria) than is true of Clinton Reservoir, and as in the case of chlorophyll *a*, this difference may be due to the presence of high concentrations of suspended soils.

7. Our analyses suggest that efforts to maintain mean total phosphorus concentrations below 110 ugP/L, and mean chlorophyll a concentrations below 11 ug/L, at all sites in the water body should maintain mean geosmin concentrations below the limit of human detection (5 ng/L) in drinking water obtained from Cheney Reservoir.

8. Geosmin and MIB in Cheney Reservoir waters are likely to be very labile, and subject to rapid biodegradation under *in situ* conditions.

9. Watershed-level nutrient loading controls that are designed to minimize total algal biomass at all sites in Cheney Reservoir may be most effective management tool to limit the frequency and likelihood of taste and odor events in Cheney Reservoir, because the biomass of all potential taste and odor-forming species of algae will be maintained at the lowest possible levels.

10. Future efforts to understand the ecological mechanisms leading to diatom dominance over blue-green algae in Cheney Reservoir will contribute not only to effective water quality management for this drinking water supply, but also will contribute significantly to our ability to predict and manage geosmin-related taste and odor problems in other Kansas impoundments.

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Figure Headings

Fig. 1. Plot of subjective odor scores versus chlorophyll concentrations in six Eastern Kansas reservoirs (data from Table 1 and Table 3 in Arruda and Fromm 1989).

Fig. 2. Relationship between November geosmin concentrations and mean total phosphorus concentrations at 12 sampling stations in Clinton Reservoir, Kansas (deNoyelles et al., unpublished data).

Fig. 3. Generalized empirical modeling framework for the management of eutrophication (see text).

Fig. 4. Map of Cheney Reservoir, showing the six proposed permanent sampling sites (shown as solid circles; modified from Fig. 1 in U.S. Fish and Wildlife Service 1996).

Fig. 5. Relationship between mean concentrations of chlorophyll *a* and total phosphorus at the six permanent sampling stations, August 1999-October 2000.

Fig. 6. Relationship between mean concentrations of chlorophyll *a* and total nitrogen at the six permanent sampling stations, August 1999-October 2000.

Fig. 7. Relationship between chlorophyll *a* and total phosphorus in Missouri reservoirs and Cheney Reservoir. Missouri data from Jones and Kowlton (1993); 1994-1995 Cheney Reservoir data from U.S. Fish and Wildlife (1996).

Fig. 8. Relationship between mean Secchi disk transparency and mean concentrations of chlorophyll *a* at the six permanent sampling sites, August 1999-October 2000.

Fig. 9. Relationship between mean vertical light extinction (K, m^{-1}) and mean concentrations of chlorophyll *a* at the six permanent sampling sites, August 1999-October 2000.

Fig. 10. Relationship between mean Secchi disk transparency and mean turbidity at the six permanent sampling sites, August 1999-October 2000.

Fig. 11. Relationship between mean vertical light extinction (K, m^{-1}) and mean turbidity at the six permanent sampling sites, August 1999-October 2000.

Fig. 12. Relationship between percent blue-green algae (%BG) and total algal biomass in Cheney Reservoir and 34 additional Kansas reservoirs. Kansas reservoir data from Carney (2001).

Fig. 13. Time series measurements of the biomass of *Cyclotella* in Cheney Reservoir, August 1999-October 2000.

Fig. 14. Time series measurements of the biomass of Melosira in Cheney Reservoir, August 1999-October 2000.

Fig. 15. Time series measurements of the biomass of *Anabaena* in Cheney Reservoir, August 1999-October 2000.

Fig. 16. Time series measurements of the biomass of *Aphanizomenon* in Cheney Reservoir, August 1999-October 2000.

Fig. 17. Correlation between mean concentrations of geosmin and mean chlorophyll *a* concentrations in Cheney Reservoir, August 1999-October 2000.

Fig. 18. Correlation between mean concentrations of geosmin and mean total phosphorus concentrations in Cheney Reservoir, August 1999-October 2000.

Fig. 19. Correlation between peak geosmin concentrations and mean blue-green algal biomass in Clinton Reservoir and Cheney Reservoir (Clinton Reservoir data from S. Wang, D. Huggins, and F. deNoyelles, unpubl. data)

Fig. 20. Relationship between mean Actinomycete abundance and mean chlorophyll *a* concentrations in Cheney Reservoir, August 1999-October 2000 (all data).

Fig. 21. Relationship between mean concentrations of geosmin and mean Actinomycete abundance in Cheney Reservoir, August 1999-October 2000 (all data).

Fig. 22. Relationship between mean Actinomycete abundance and mean chlorophyll *a* concentrations in Cheney Reservoir, August 1999-October 2000 (March-October 2000 data).

Fig. 23. Relationship between mean Actinomycete abundance and mean Actinomycete abundance in Cheney Reservoir, August 1999-October 2000 (March-October 2000 data).

Fig. 24. Patterns of geosmin biodegradation in water taken from Clinton Reservoir, Cheney Reservoir, and Reservoir #2 at the Nelson Environmental Studies Area, University of Kansas.

Fig. 25. Patterns of MIB biodegradation in water taken from Clinton Reservoir, Cheney Reservoir, and Reservoir #2 at the Nelson Environmental Studies Area, University of Kansas (samples from 25 February 2000).

Fig. 26. Patterns of geosmin biodegradation in water taken from Clinton Reservoir, Cheney Reservoir, and Reservoir #2 at the Nelson Environmental Studies Area, University of Kansas (samples from 12 June 2000).

Fig. 2

Trends in Geosmin, Clinton Reservoir (May-December mean values)

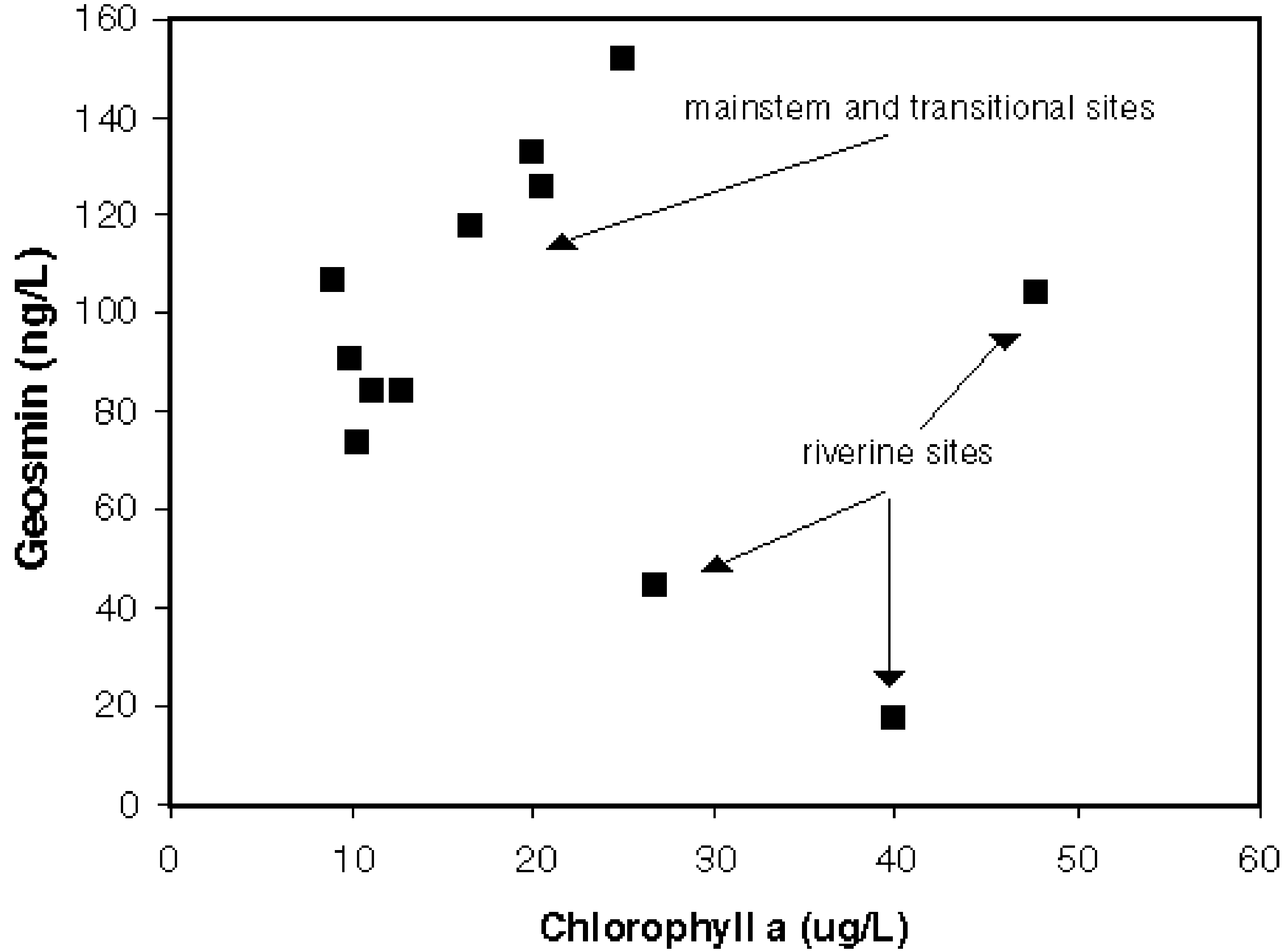
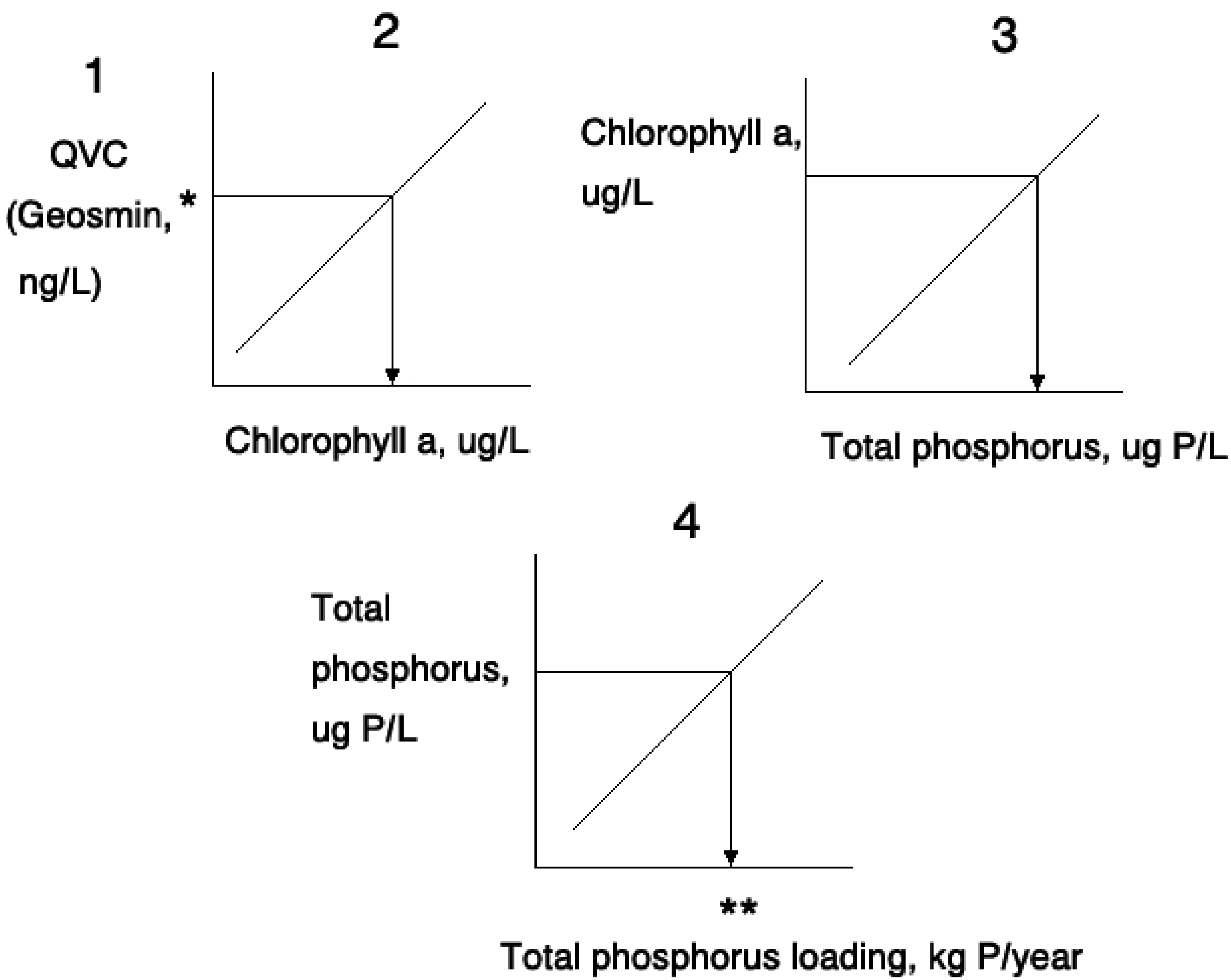


Fig. 3


1
2
3
4
QVC
(Geosmin,
ng/L)
*
Chlorophyll a, ug/L
Chlorophyll a,
ug/L
Total phosphorus, ug P/L
Total
phosphorus,
ug P/L
**
Total phosphorus loading, kg P/year

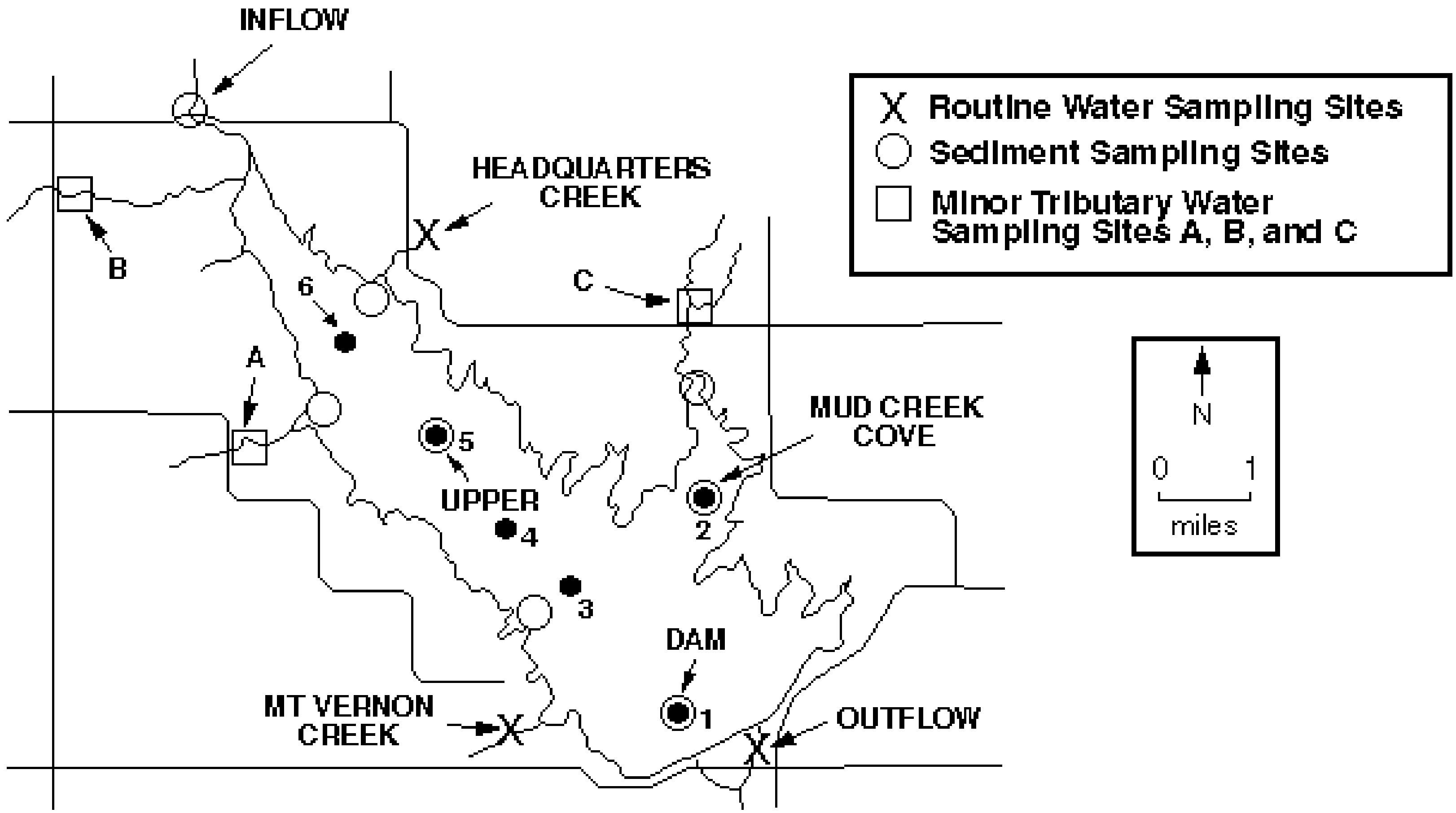
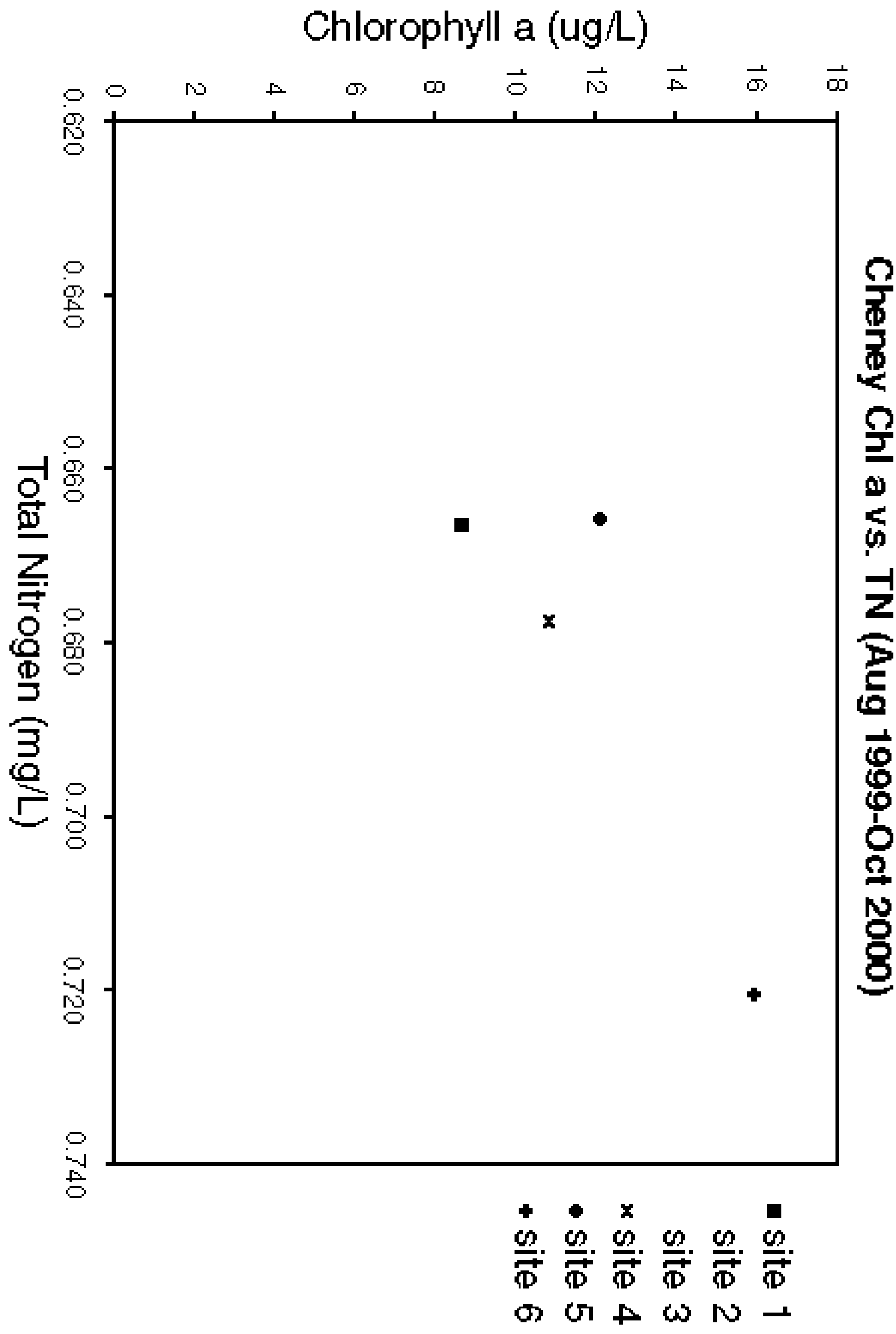


Figure 4: Map of Cheney Reservoir showing locations of water and sediment sampling sites

Fig. 5



Cheney Chl a vs. TN (Aug 1999-Oct 2000)
Chlorophyll a (ug/L)
0
2
4
6
8
10
12
14
16
18
0.620
0.640
0.660
0.680
0.700
0.720
0.740
Total Nitrogen (mg/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 6

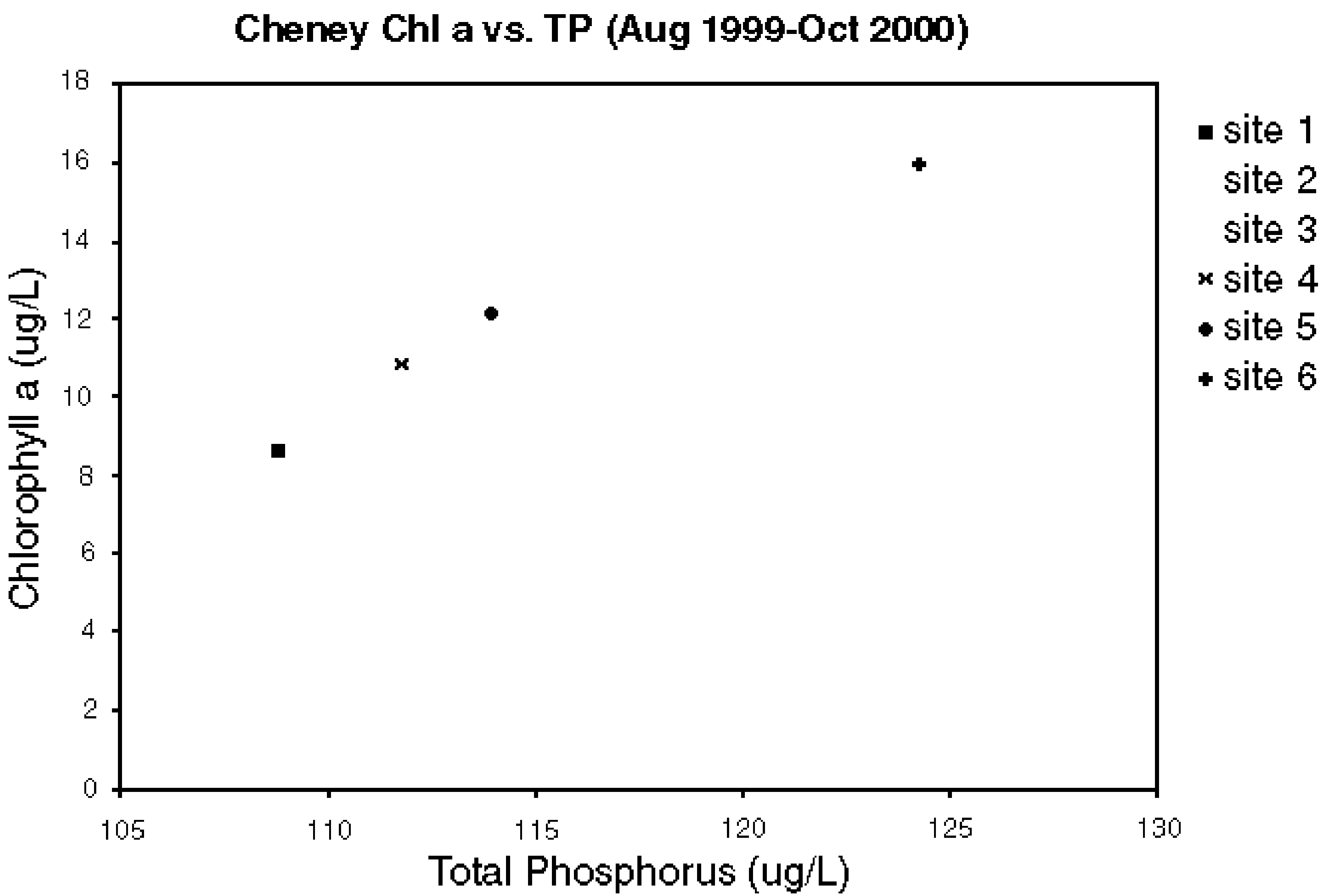

Cheney Chl a vs. TP (Aug 1999-Oct 2000)
Chlorophyll a (ug/L)
0
2
4
6
8
10
12
14
16
18
105
110
115
120
125
130
Total Phosphorus (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 7

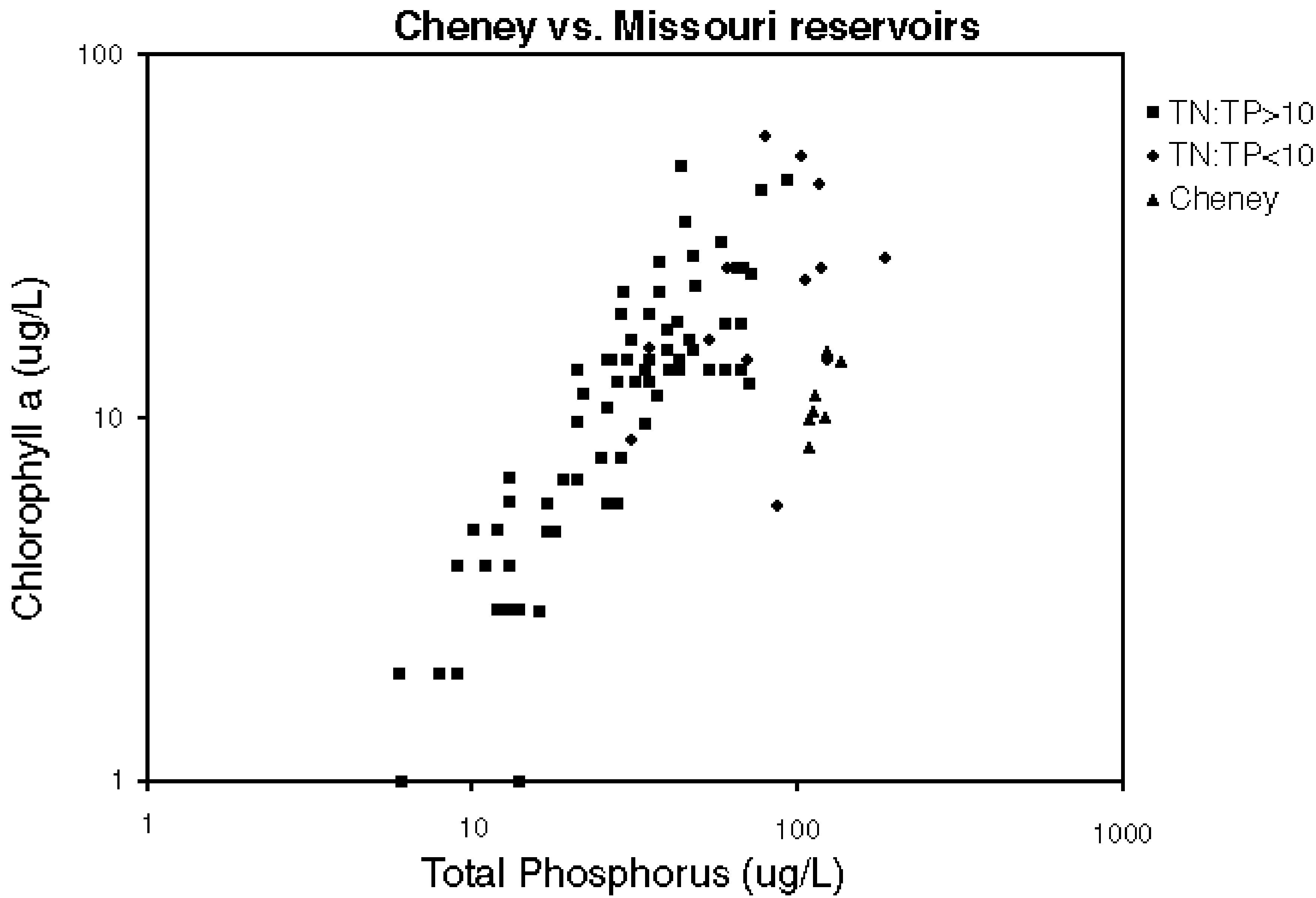
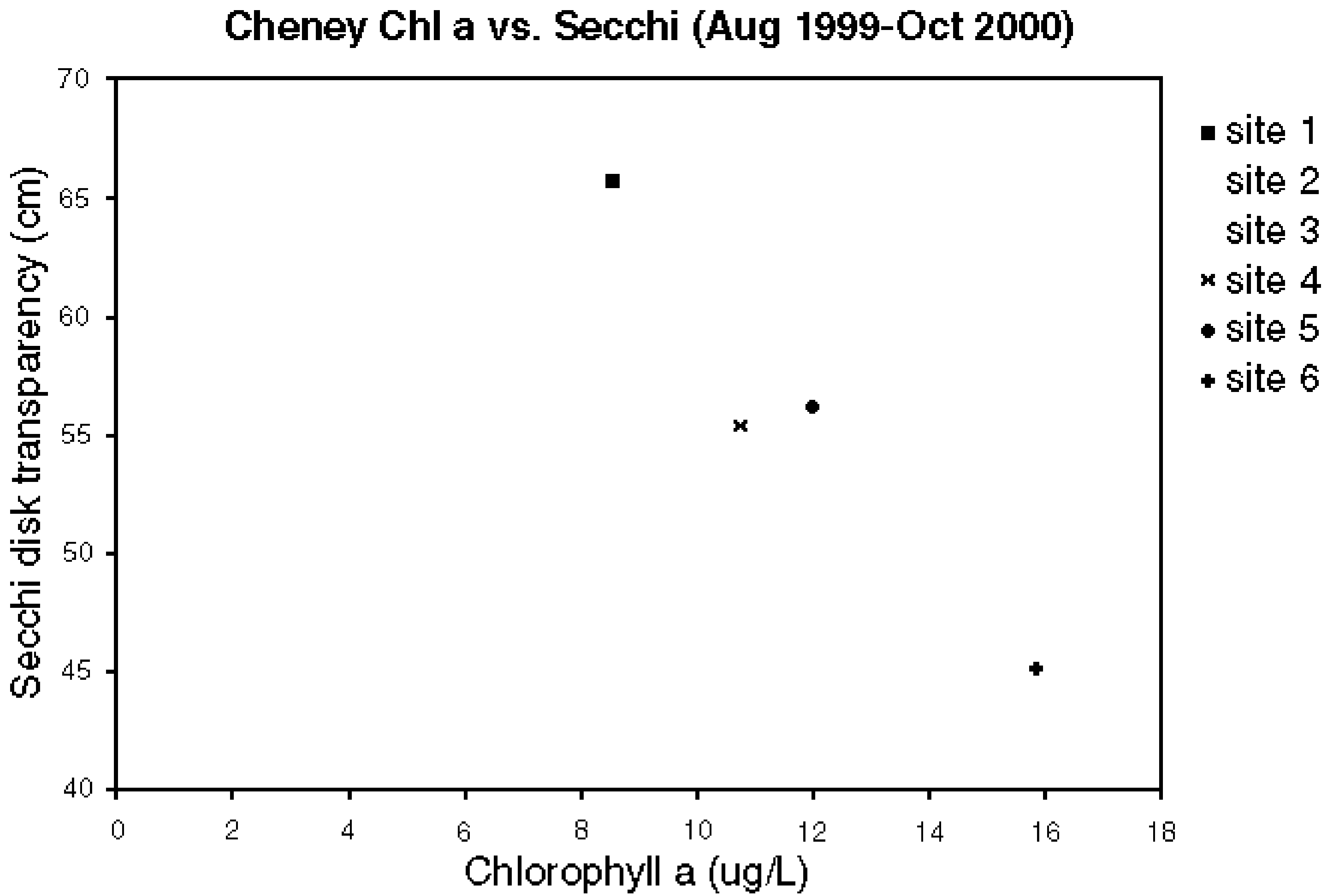
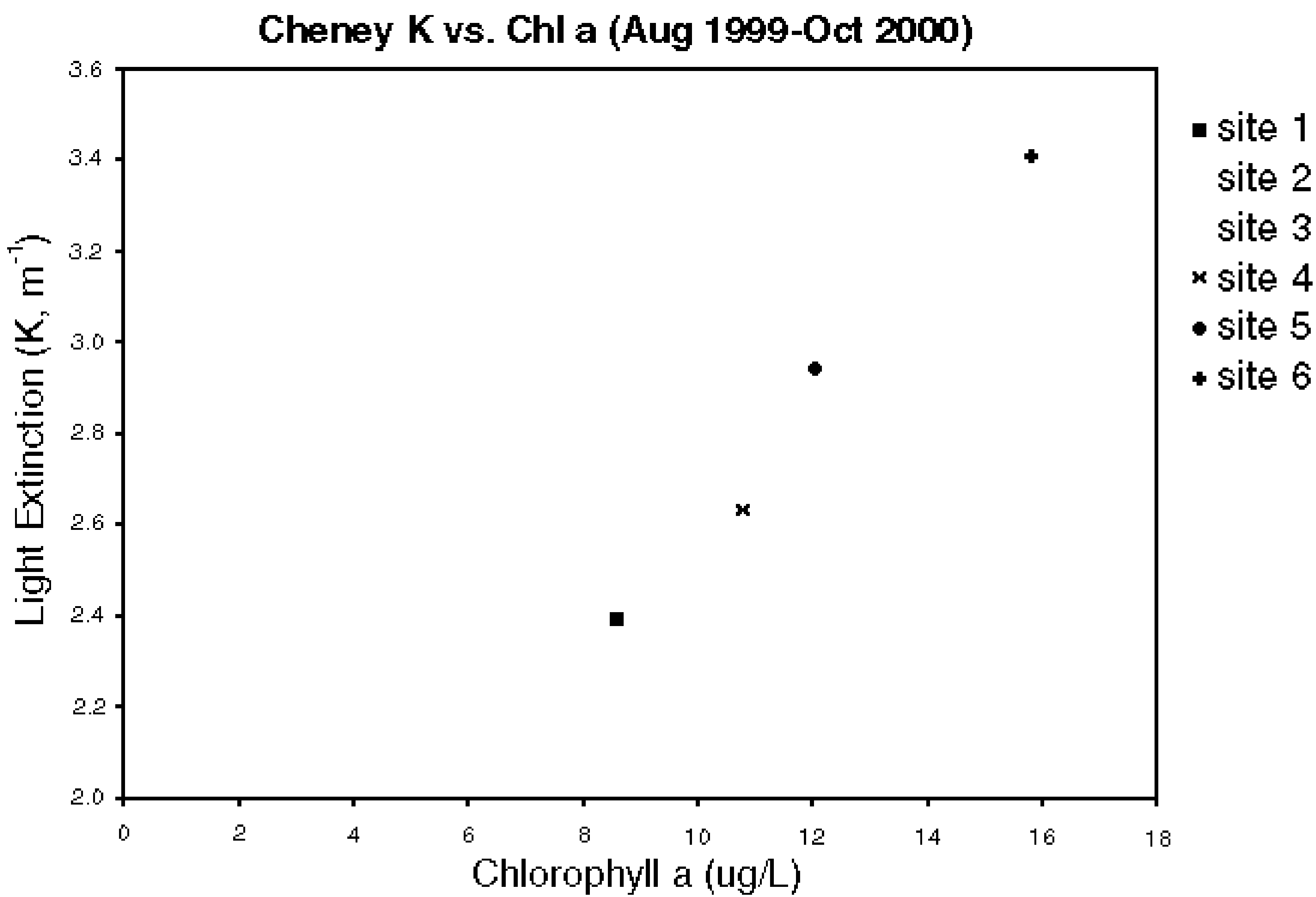

Cheney vs. Missouri reservoirs
100
10
1
Chlorophyll a (ug/L)
1
10
100
1000
Total Phosphorus (ug/L)
TN:TP>10
TN:TP<10
Cheney

Fig. 8



Cheney Chl a vs. Secchi (Aug 1999-Oct 2000)
Secchi disk transparency (cm)
70
65
60
55
50
45
40
0
2
4
6
8
10
12
14
16
18
Chlorophyll a (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 9



Cheney K vs. Chl a (Aug 1999-Oct 2000)
Light Extinction (K, m-1)
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
0
2
4
6
8
10
12
14
16
18
Chlorophyll a (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 10

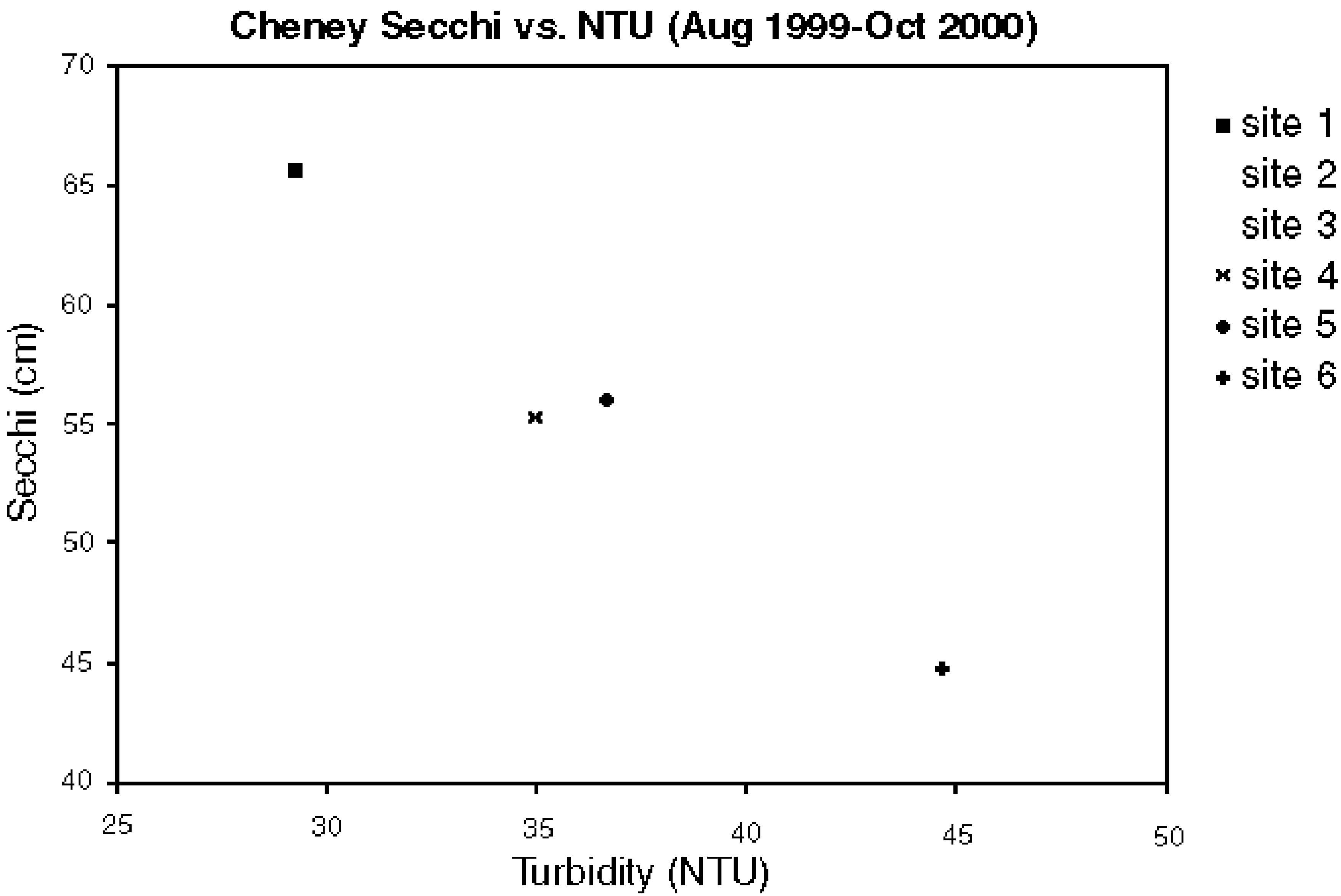
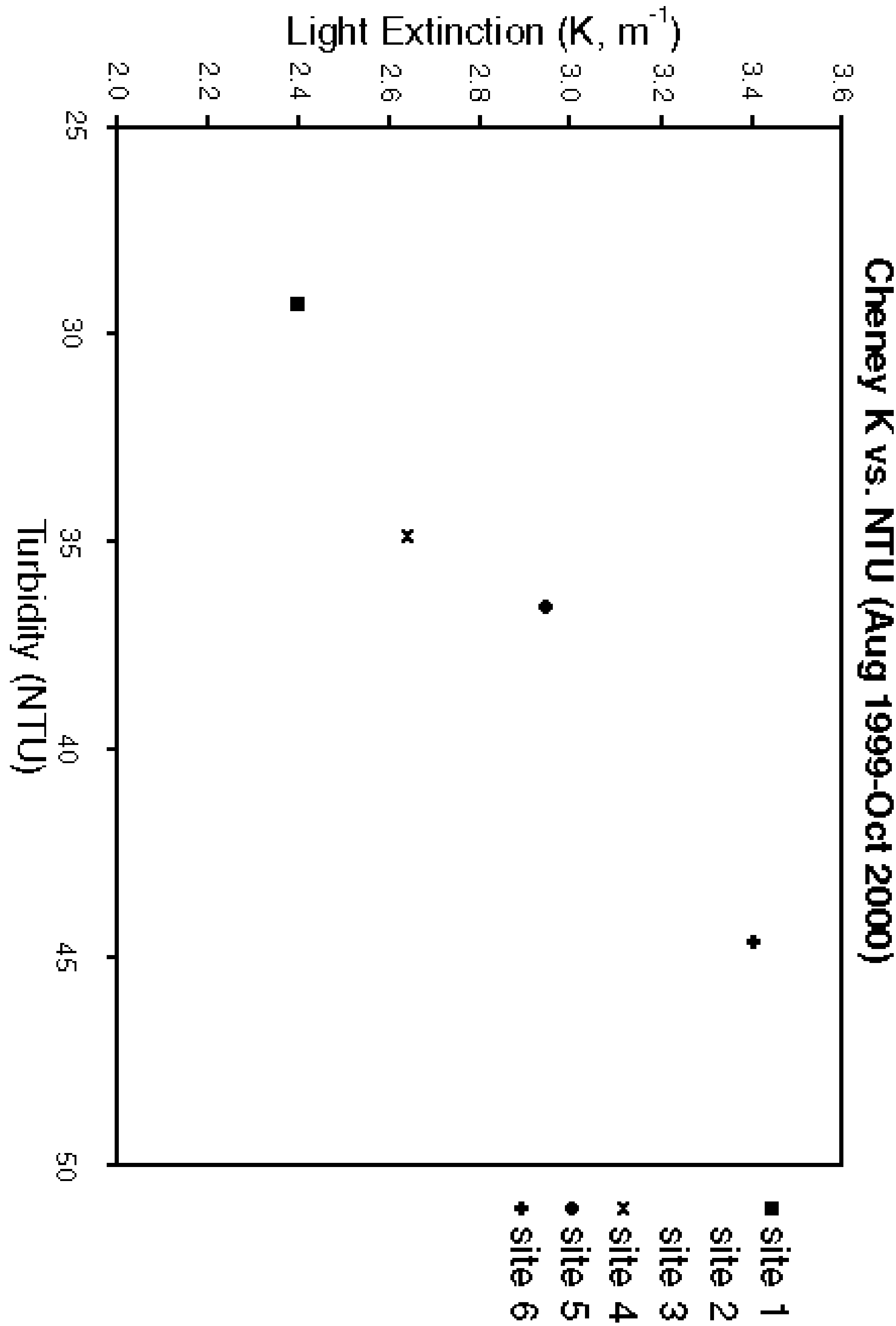

Cheney Secchi vs. NTU (Aug 1999-Oct 2000)
Secchi (cm)
70
65
60
55
50
45
40
25
30
35
40
45
50
Turbidity (NTU)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 11



Cheney K vs. NTU (Aug 1999-Oct 2000)
Light Extinction (K, m-1)
Turbidity (NTU)
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
25
30
35
40
45
50
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 12

Blue-green algal dominance in Kansas Reservoirs

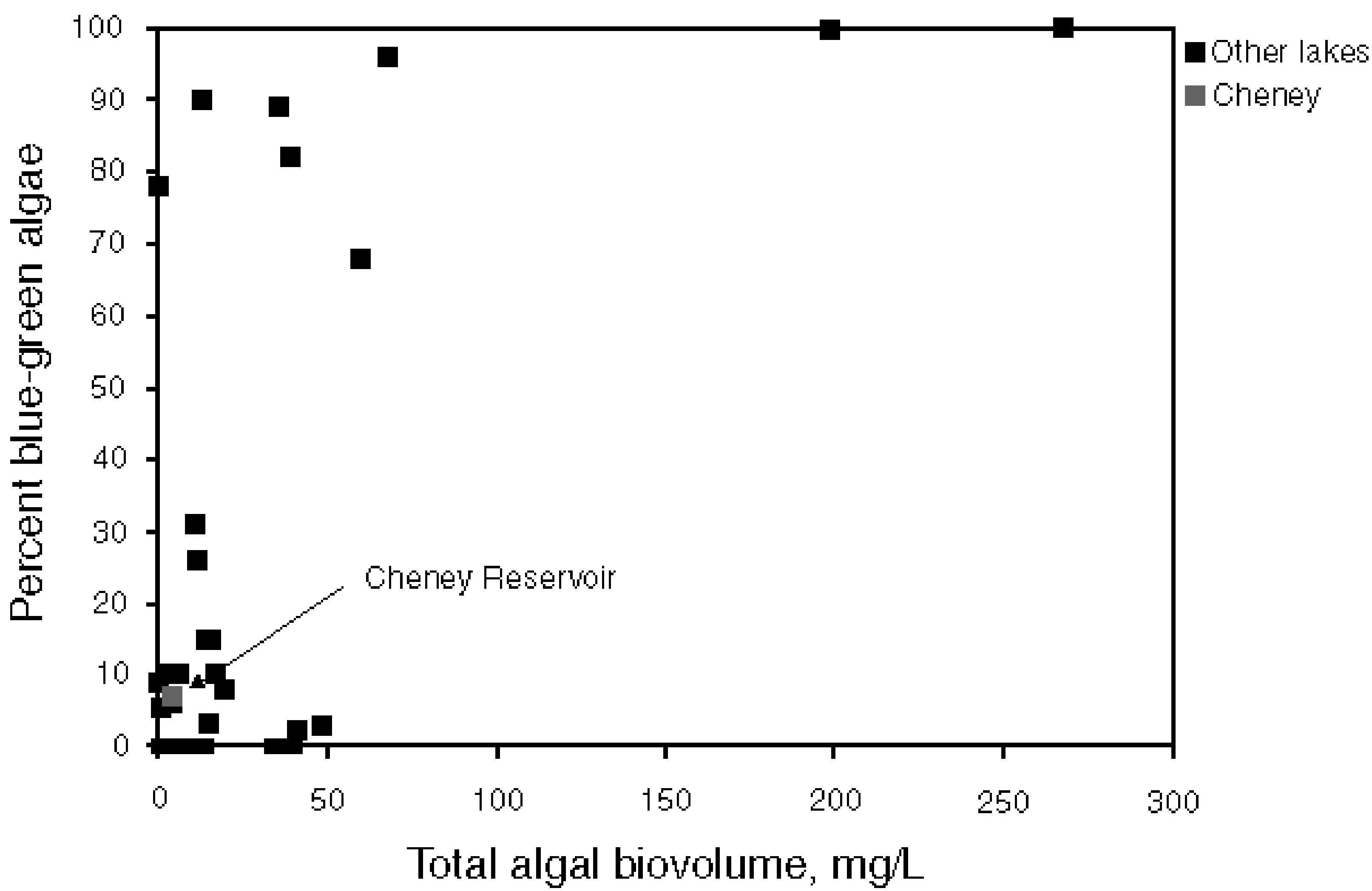


Fig. 13

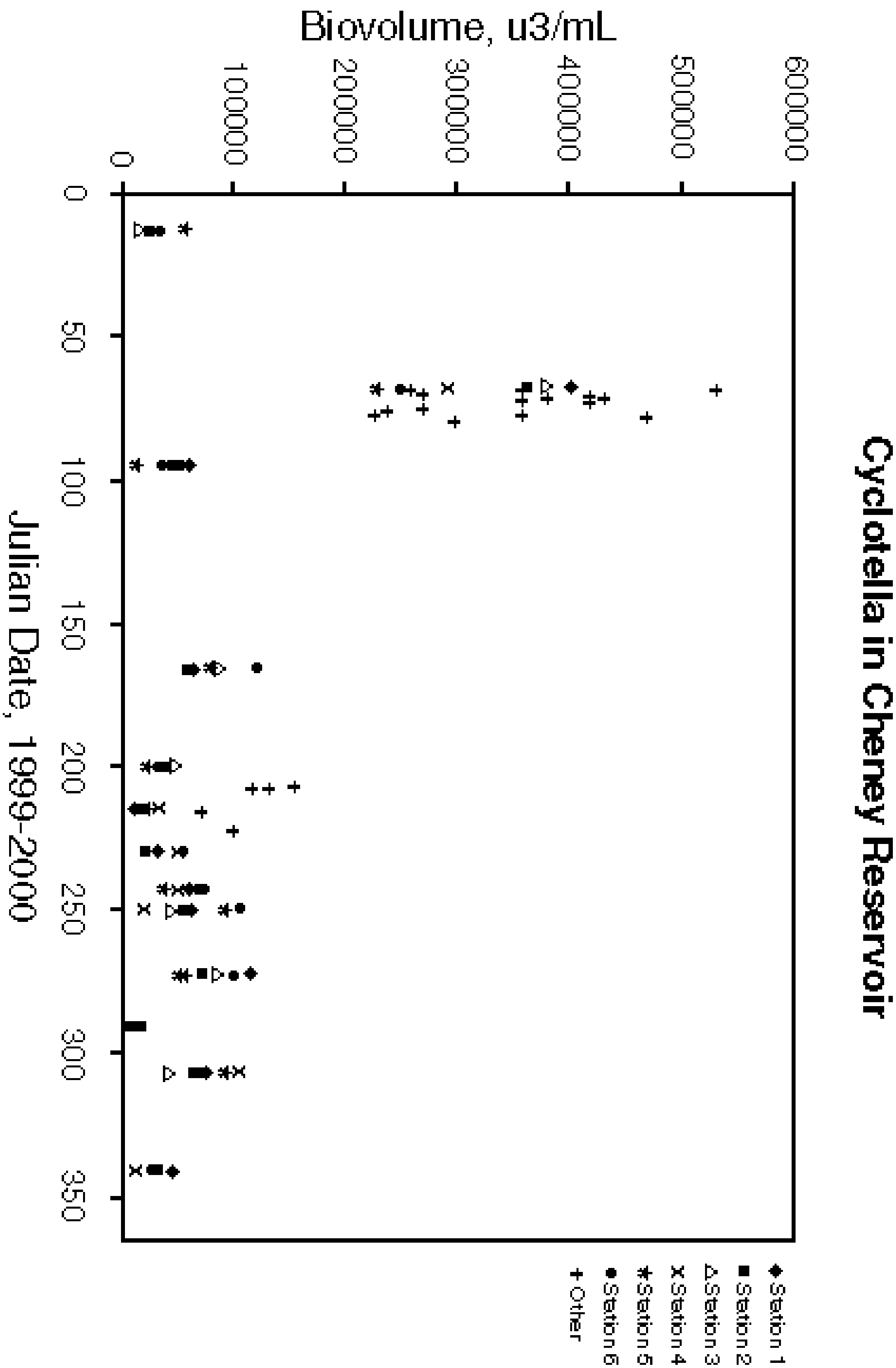
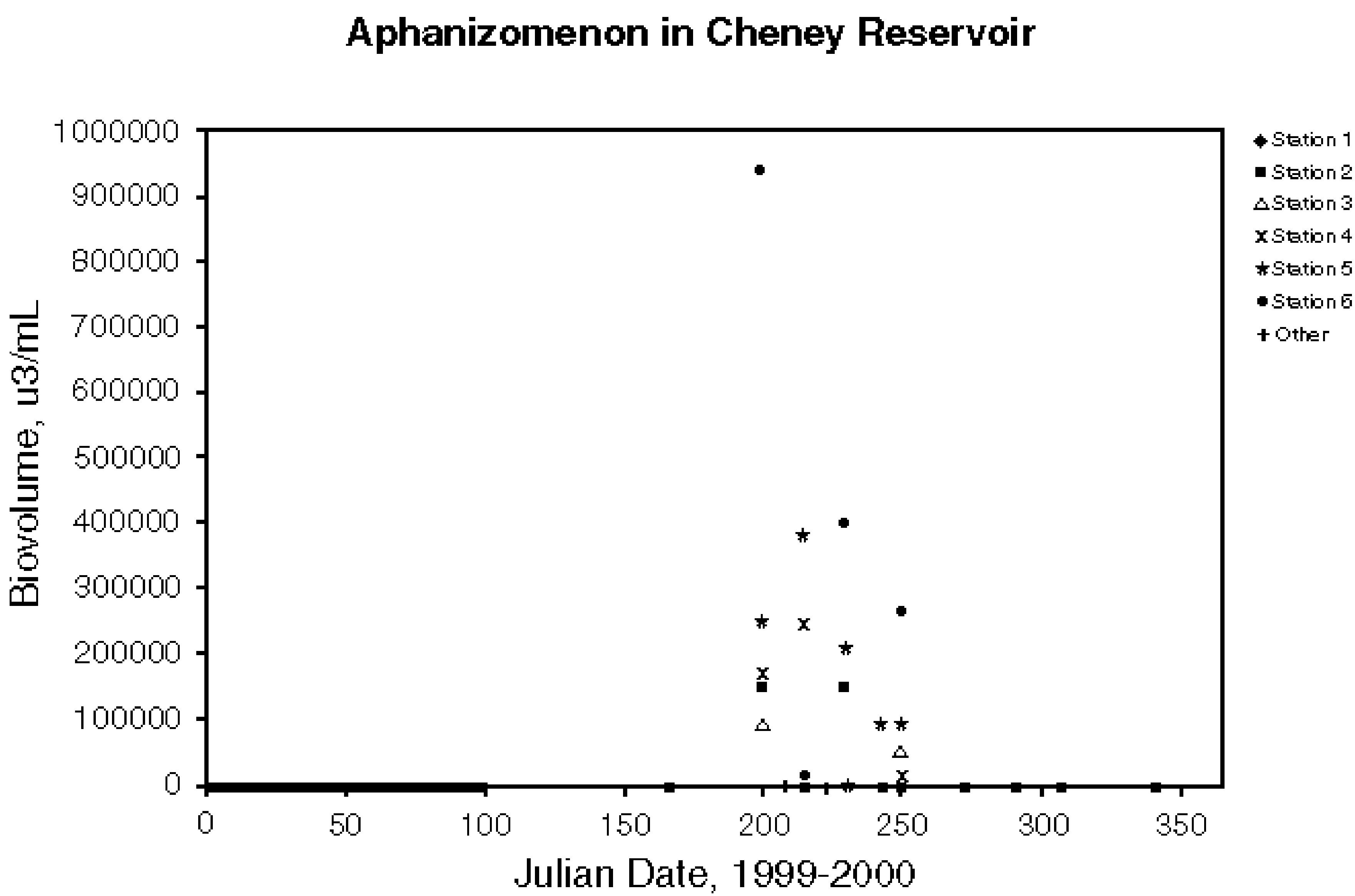

Cyclotella in Cheney Reservoir
Biovolume, u3/mL
0
100000
200000
300000
400000
500000
600000
0
50
100
150
200
250
300
350
Julian Date, 1999-2000
Station 1
Station 2
Station 3
Station 4
Station 5
Station 6
Other

Fig. 14



Aphanizomenon in Cheney Reservoir
Biovolume, u3/mL
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0
50
100
150
200
250
300
350
Julian Date, 1999-2000
Station 1
Station 2
Station 3
Station 4
Station 5
Station 6
Other

Fig. 15

Anabaena in Cheney Reservoir

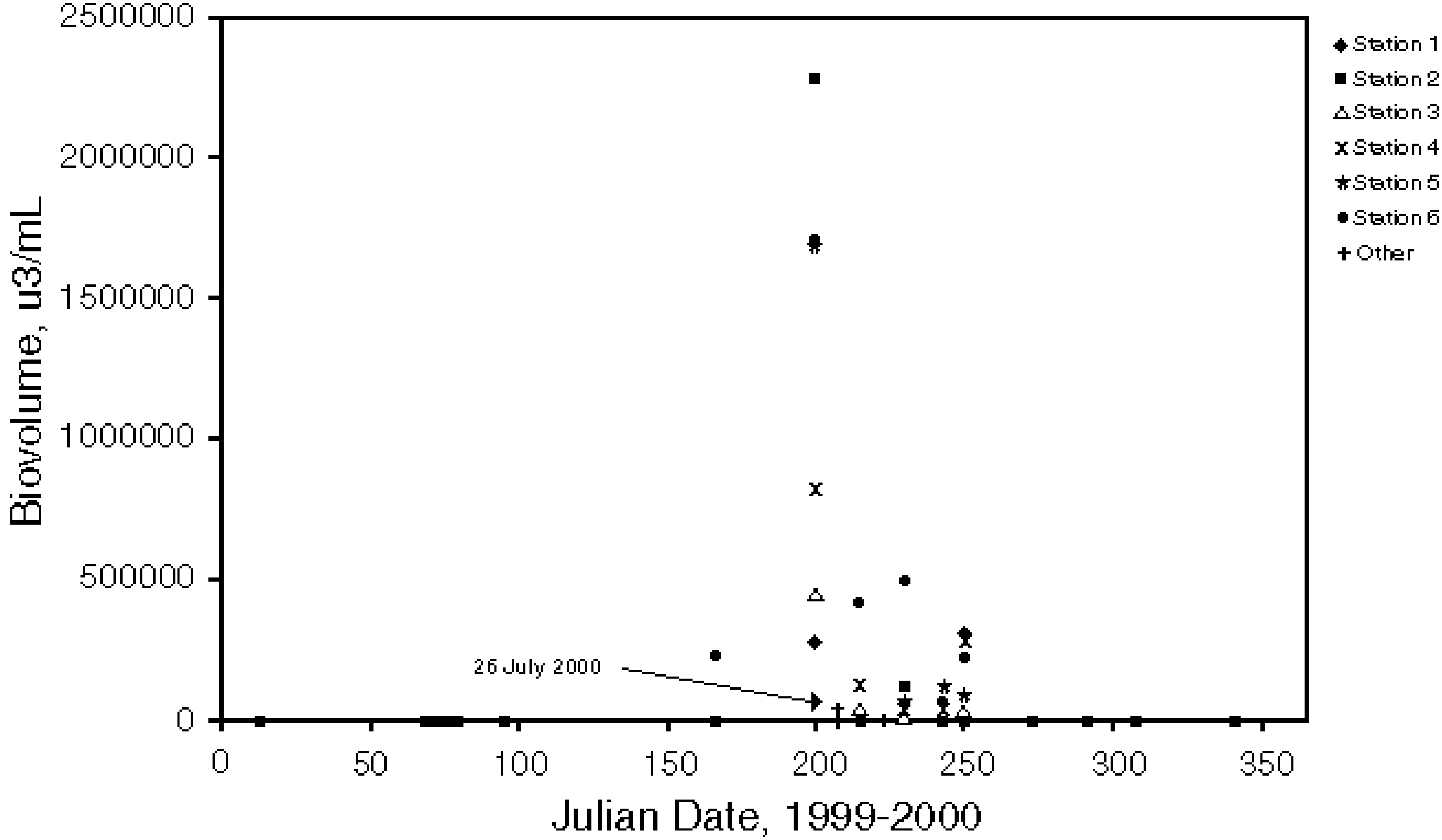
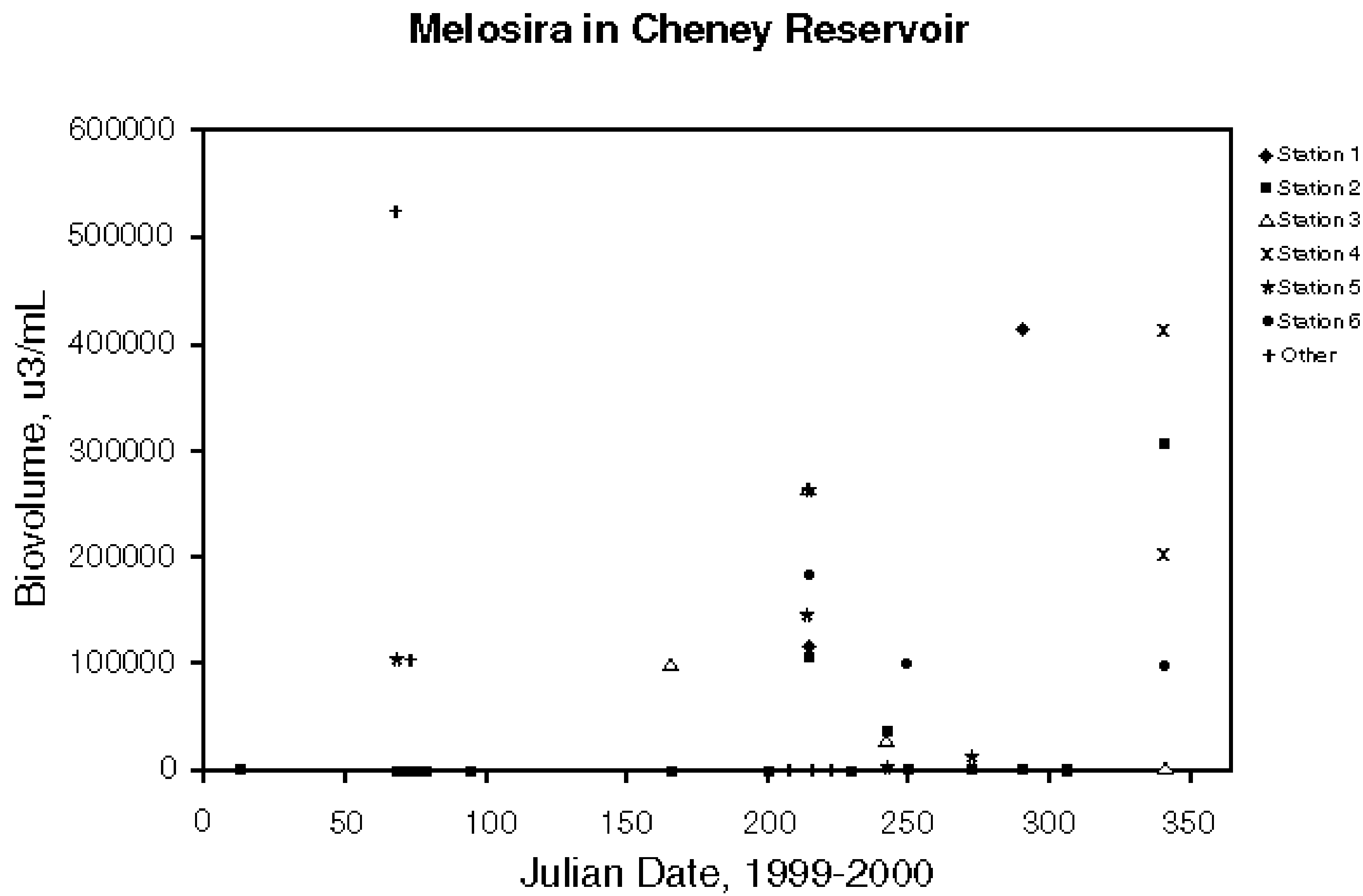
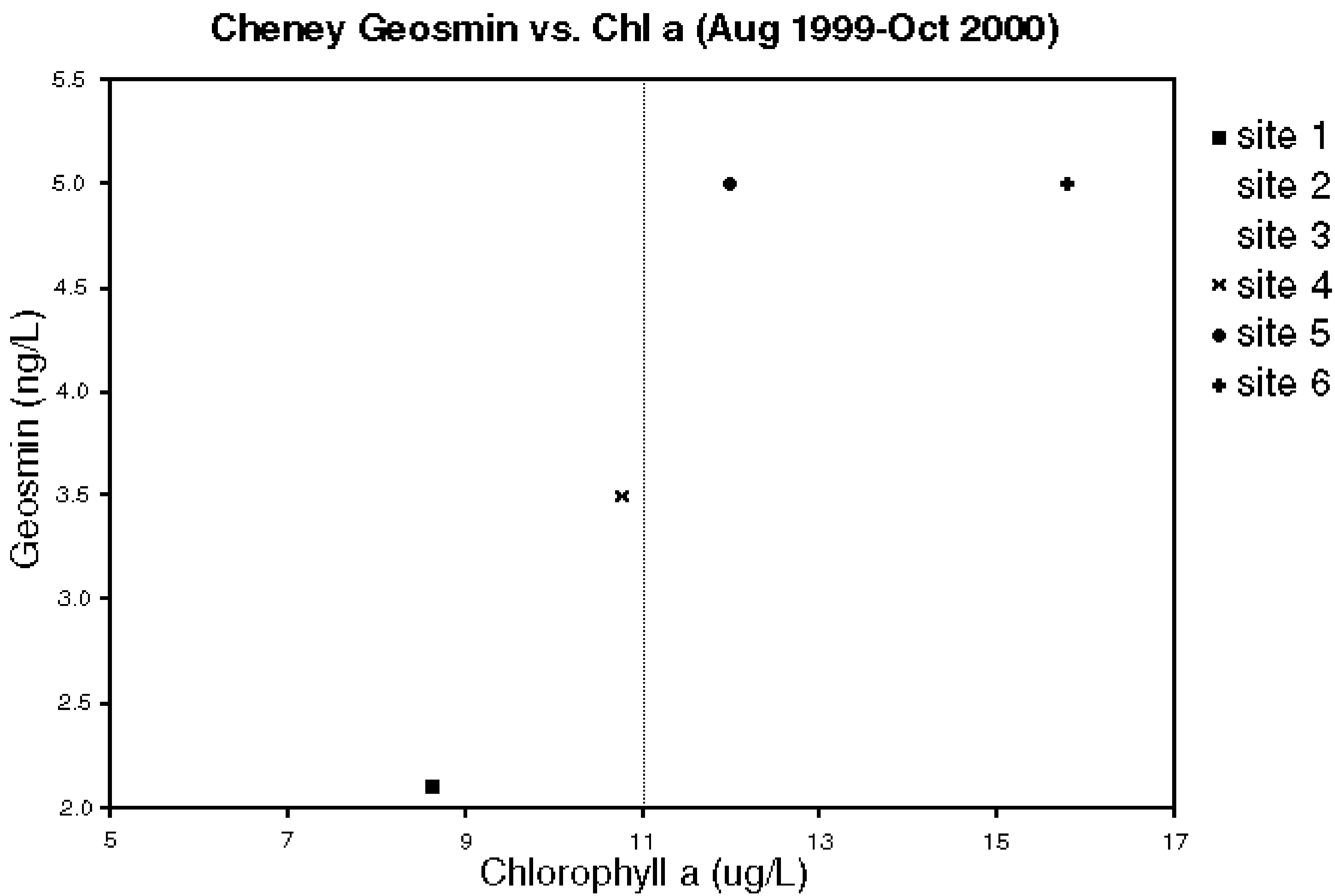


Fig. 16



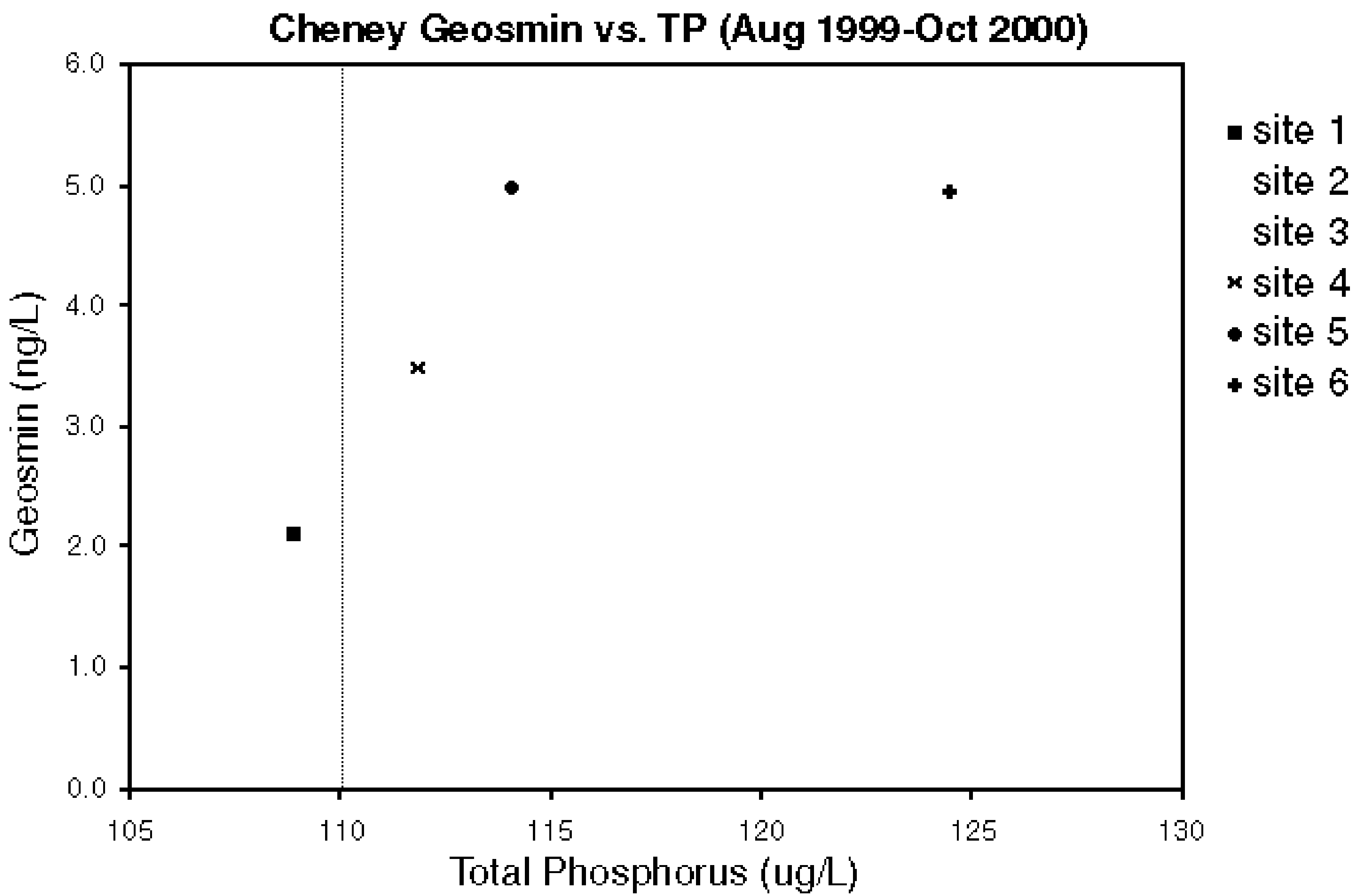
Melosira in Cheney Reservoir
Biovolume, u3/mL
600000
500000
400000
300000
200000
100000
0
0
50
100
150
200
250
300
350
Julian Date, 1999-2000
Station 1
Station 2
Station 3
Station 4
Station 5
Station 6
Other

Fig. 17



Cheney Geosmin vs. Chl a (Aug 1999-Oct 2000)
Geosmin (ng/L)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
5
7
9
11
13
15
17
Chlorophyll a (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 18



Cheney Geosmin vs. TP (Aug 1999-Oct 2000)
Geosmin (ng/L)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
105
110
115
120
125
130
Total Phosphorus (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 19

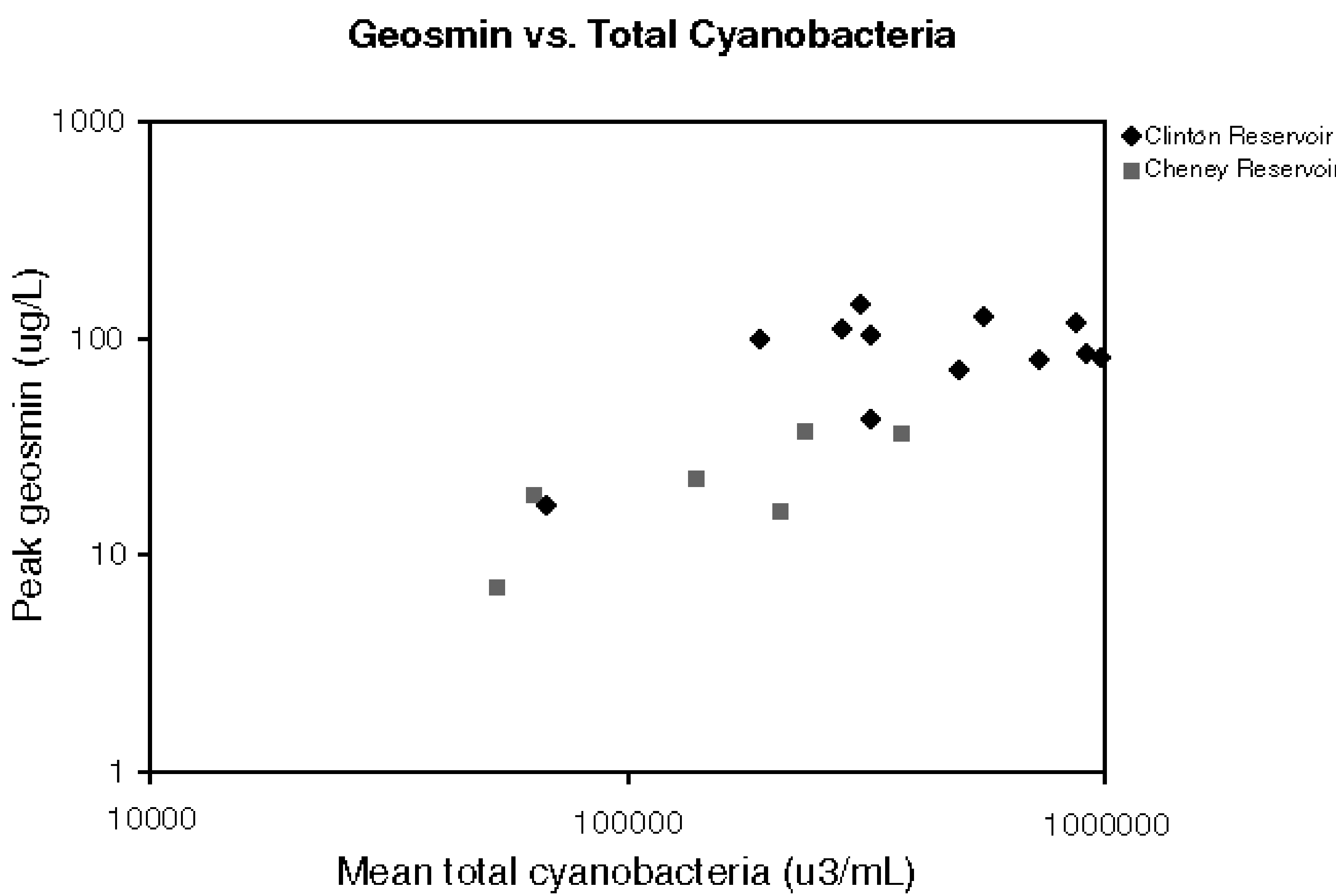

Geosmin vs. Total Cyanobacteria
Peak geosmin (ug/L)
1000
100
10
1
10000
100000
1000000
Mean total cyanobacteria (u3/mL)
Clinton Reservoir
Cheney Reservoir

Fig. 20

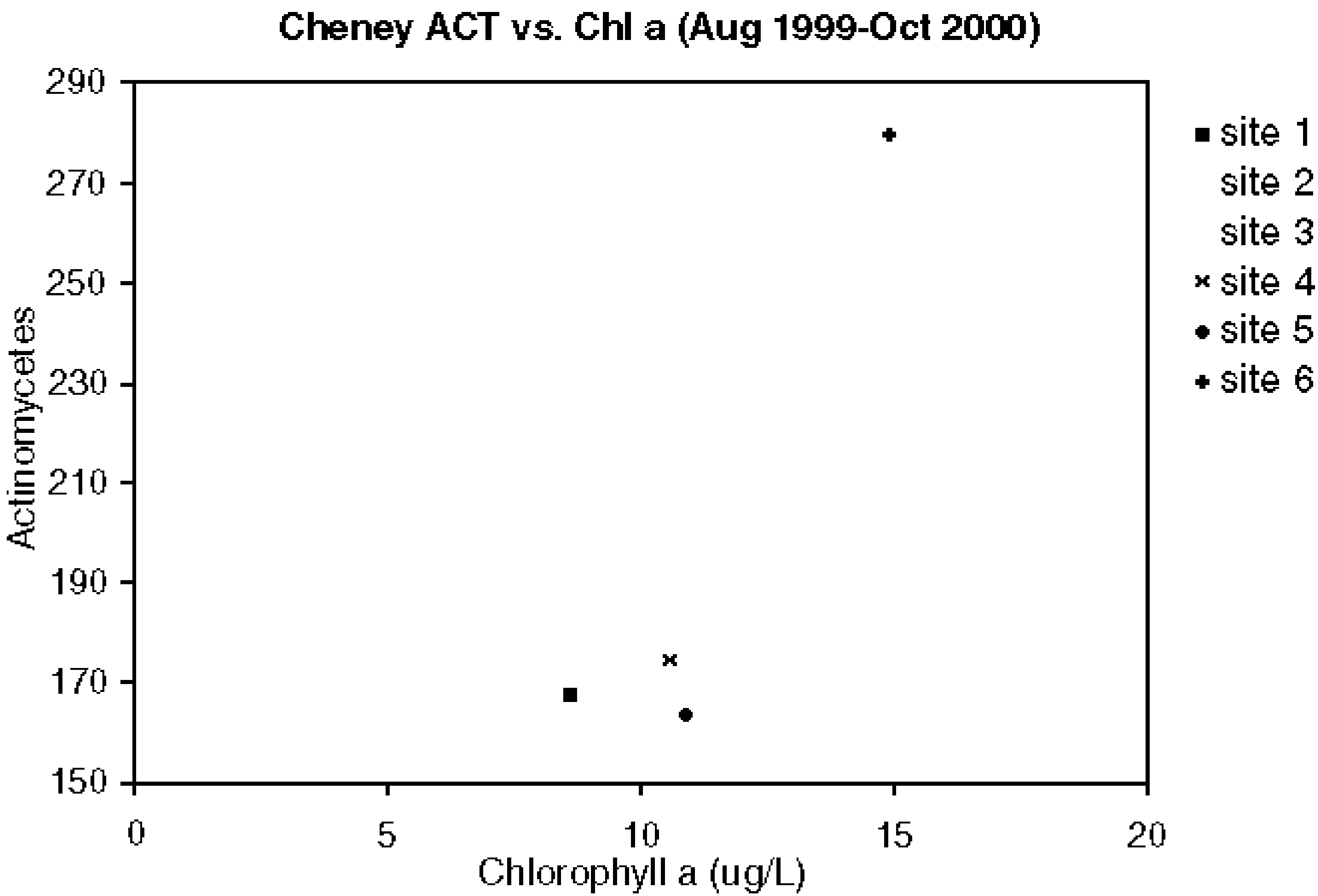
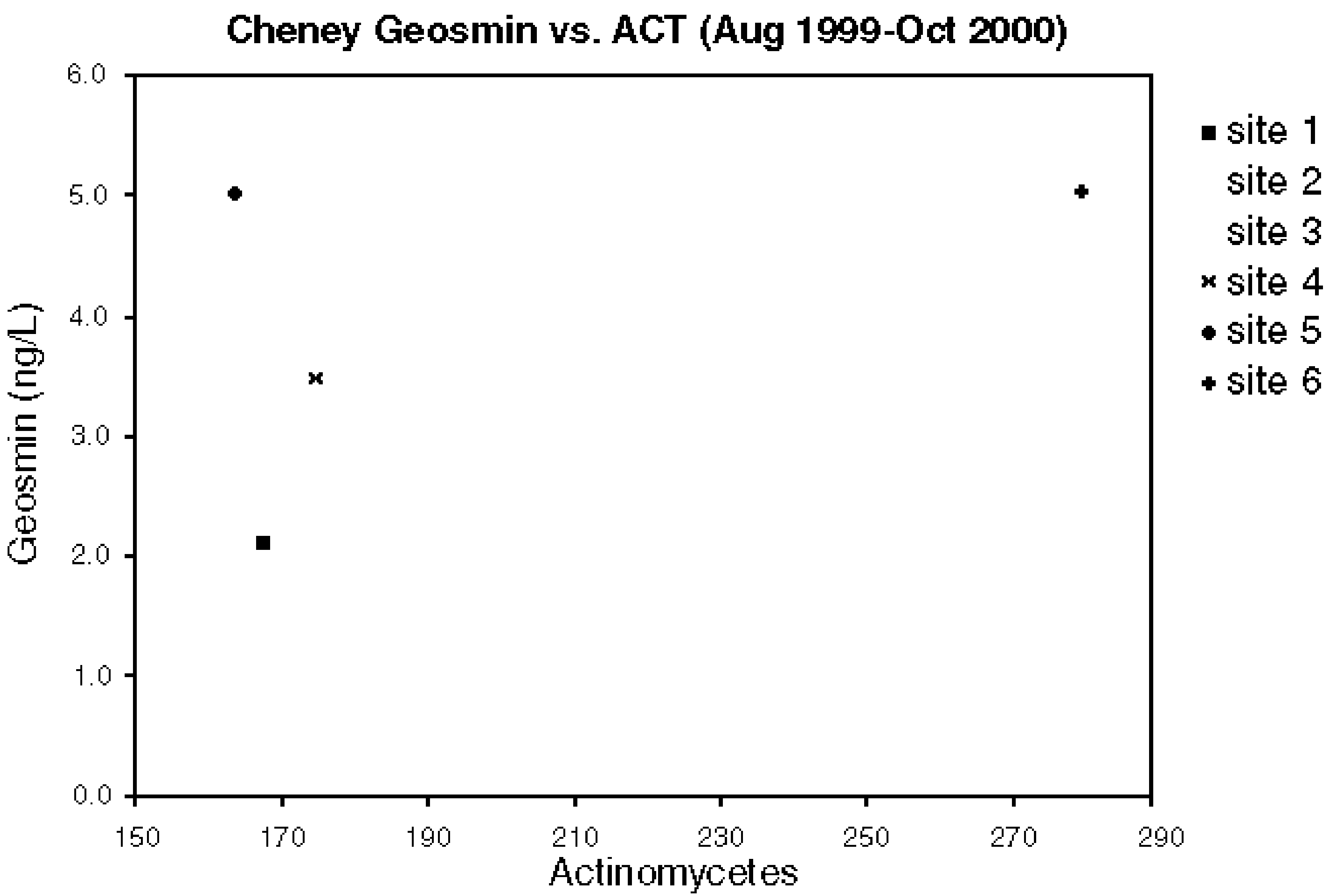

Cheney ACT vs. Chl a (Aug 1999-Oct 2000)
Actinomycetes
290
270
250
230
210
190
170
150
0
5
10
15
20
Chlorophyll a (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 21



Cheney Geosmin vs. ACT (Aug 1999-Oct 2000)
Geosmin (ng/L)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
150
170
190
210
230
250
270
290
Actinomycetes
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 22

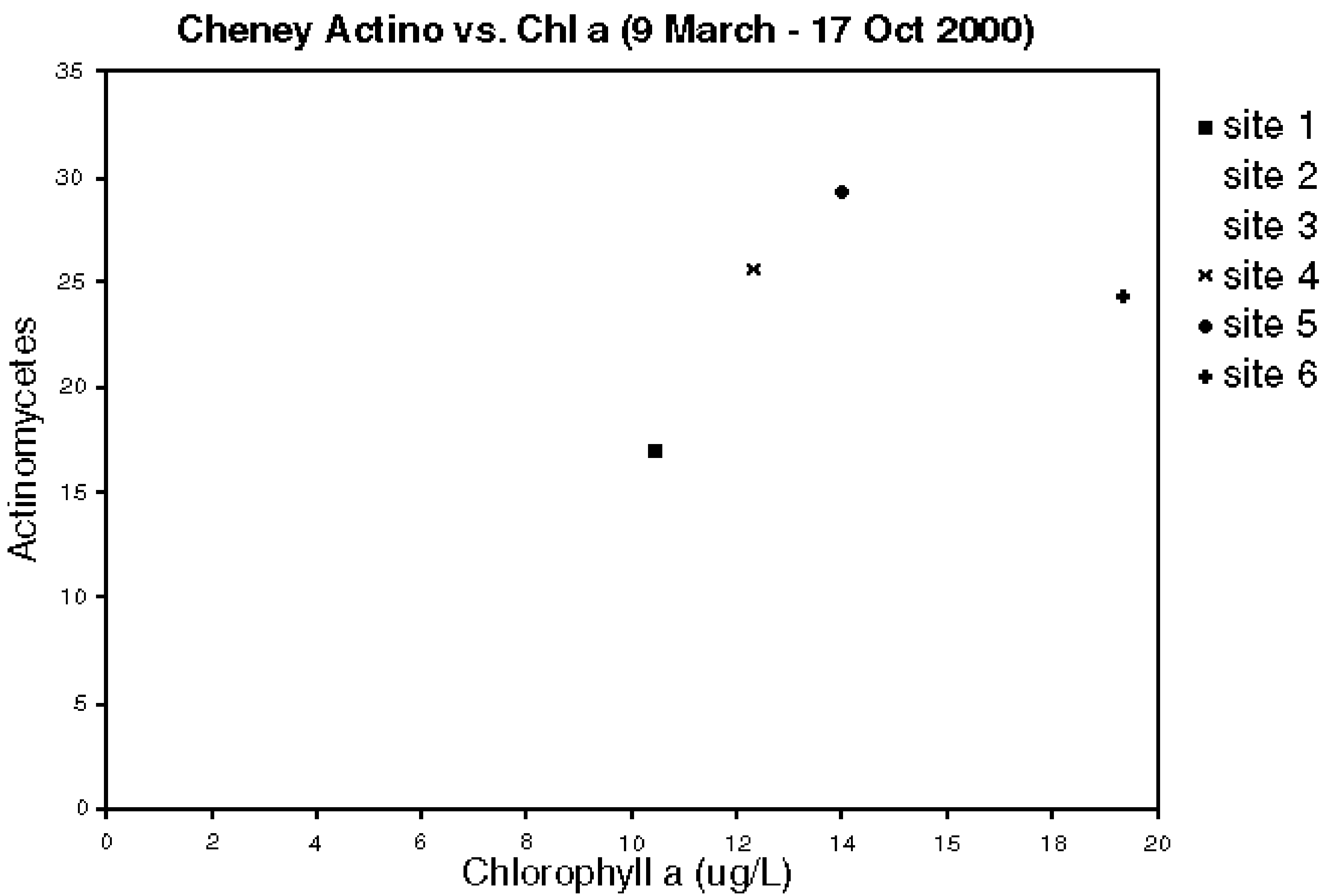
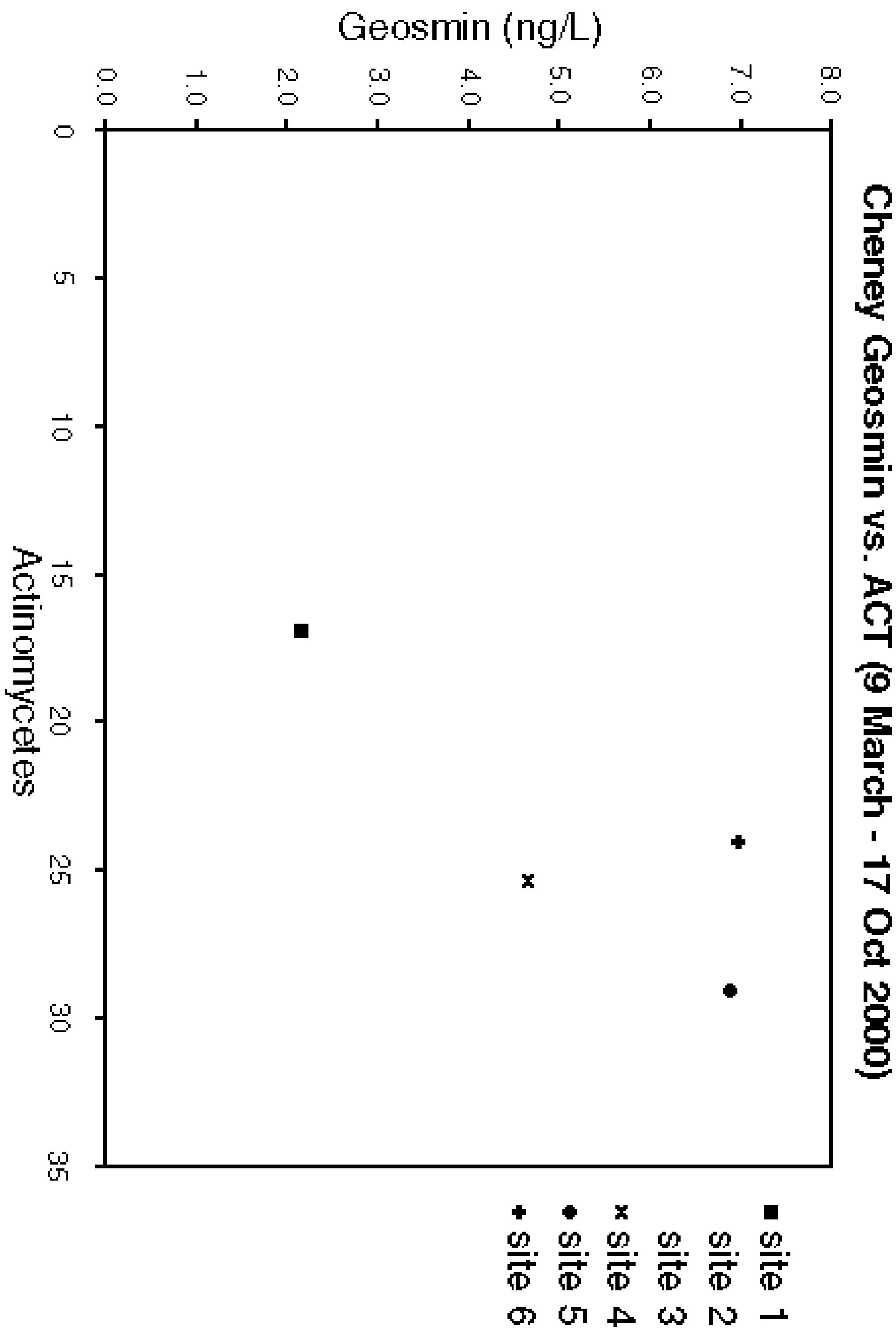
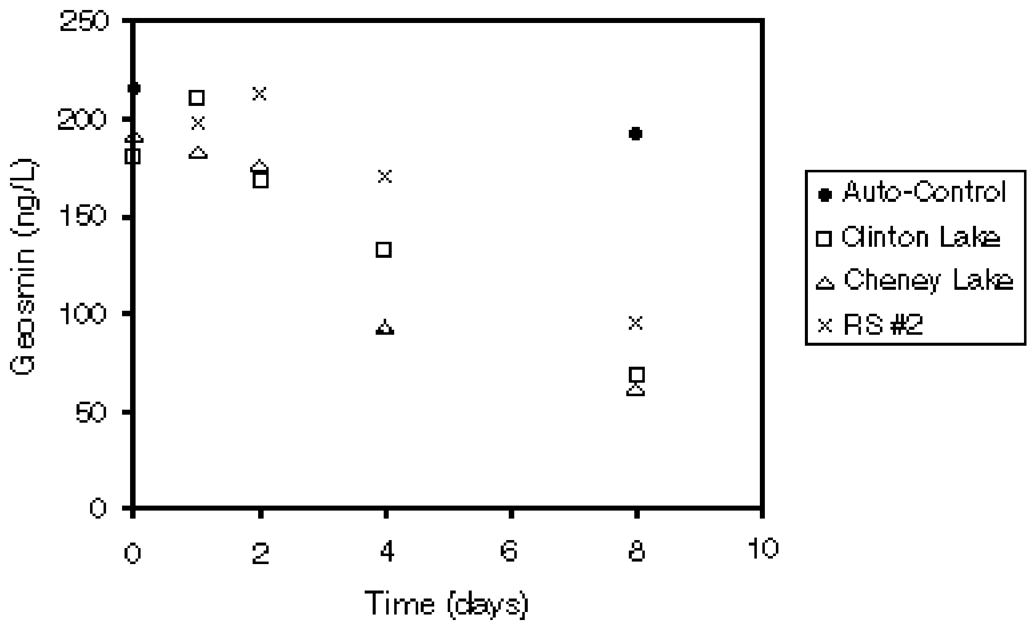

Cheney Actino vs. Chl a (9 March - 17 Oct 2000)
Actinomycetes
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14
15
18
20
Chlorophyll a (ug/L)
site 1
site 2
site 3
site 4
site 5
site 6

Fig. 23

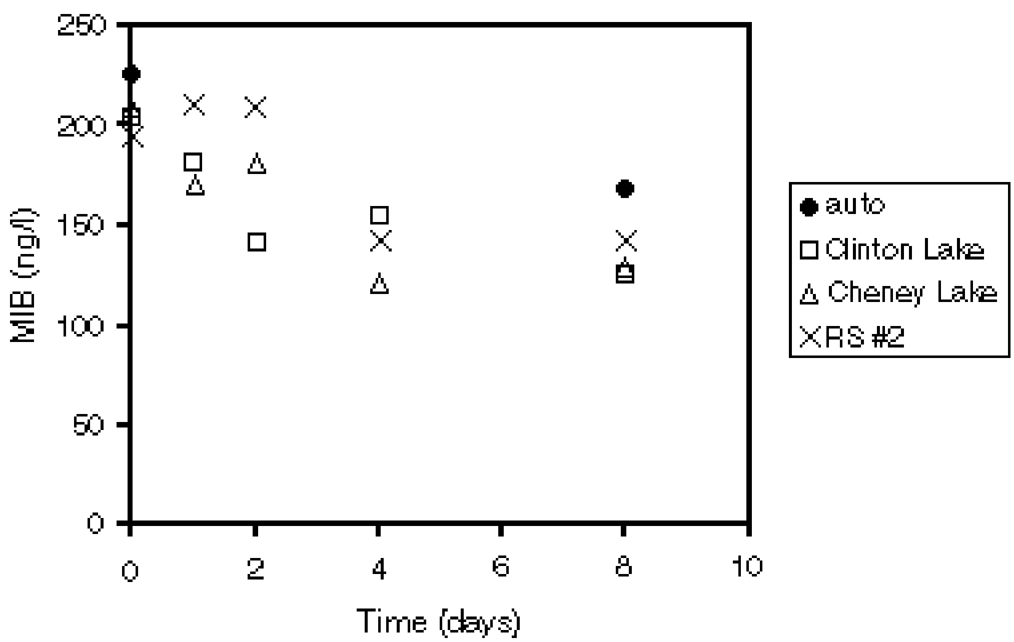


Cheney Geosmin vs. ACT (9 March - 17 Oct 2000)
Geosmin (ng/L)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Actinomycetes
0
5
10
15
20
25
30
35
site 1
site 2
site 3
site 4
site 5
site 6

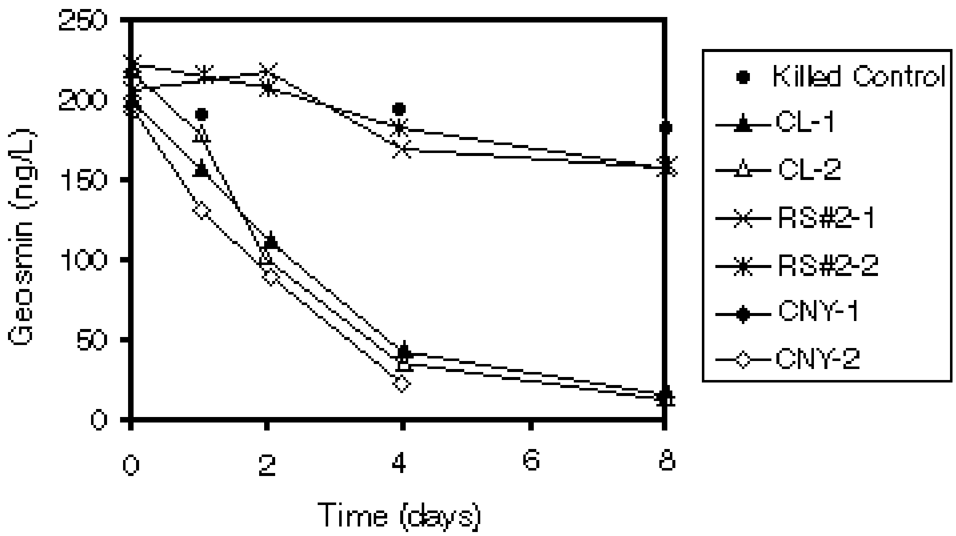
Fig. 24

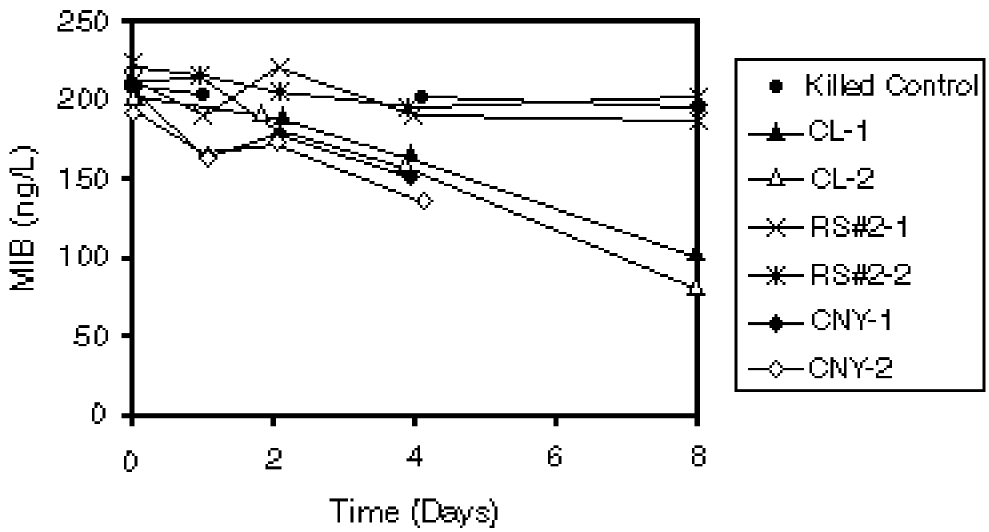


250
200
150
100
50
0
Geosmin (ng/L)
0
2
4
6
8
10
Time (days)
Auto-Control
Clinton Lake
Cheney Lake
RS #2



250
200
150
100
50
0
MIB (ng/l)
0
2
4
6
8
10
Time (days)
auto
Clinton Lake
Cheney Lake
RS #2


250
200
150
100
50
0
Geosmin (ng/L)
0
2
4
6
8
Time (days)
Killed Control
CL-1
CL-2
RS#2-1
RS#2-2
CNY-1
CNY-2


250
200
150
100
50
0
MIB (ng/L)
0
2
4
6
8
Time (Days)
Killed Control
CL-1
CL-2
RS#2-1
RS#2-2
CNY-1
CNY-2